EIC Science: (Polarized) eN Collisions

Rolf Ent - Jefferson Lab

EIC Generic Detector R&D Advisory Committee Meeting
Brookhaven National Lab, May 9^{th} 2011

NSAC 2007 Long-Range Plan:

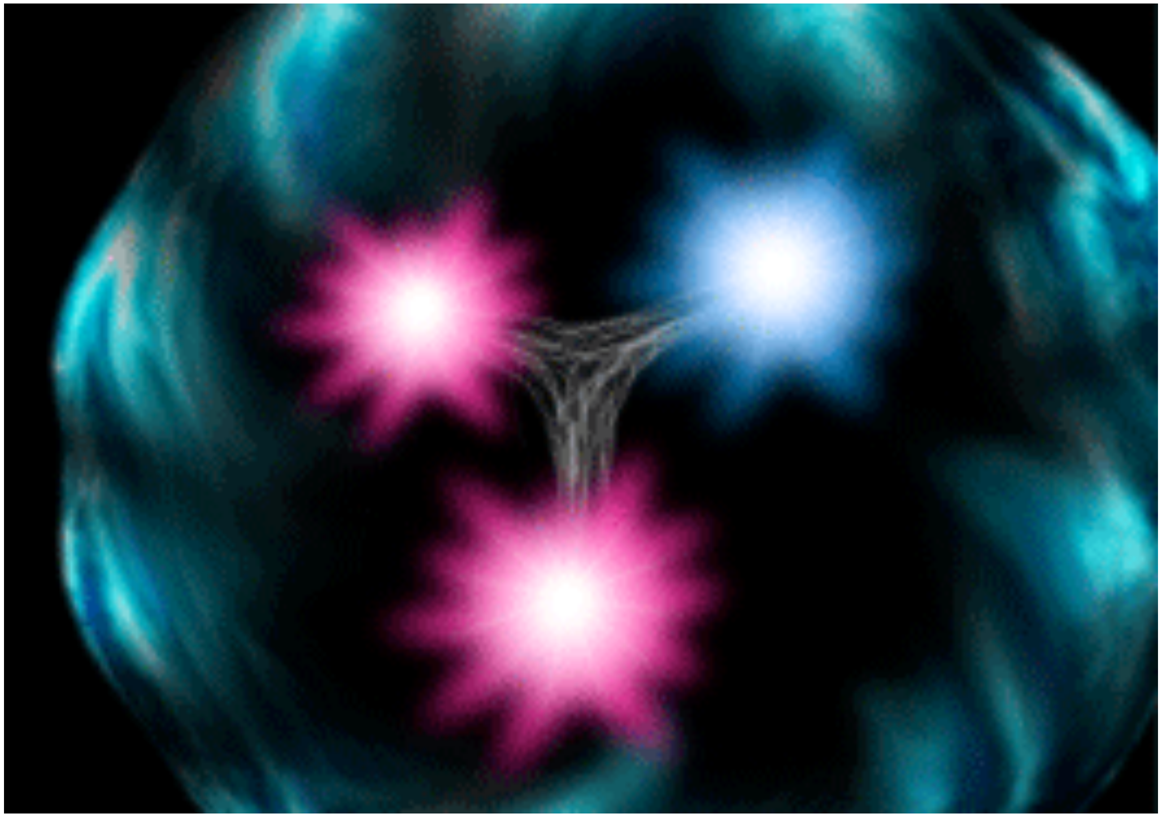
"An **Electron-Ion Collider (EIC)** with **polarized** beams has been **embraced by the U.S. nuclear science community** as embodying the vision for **reaching the next QCD frontier**.

The Structure of the Proton

Naïve Quark Model: proton = uud (valence quarks)

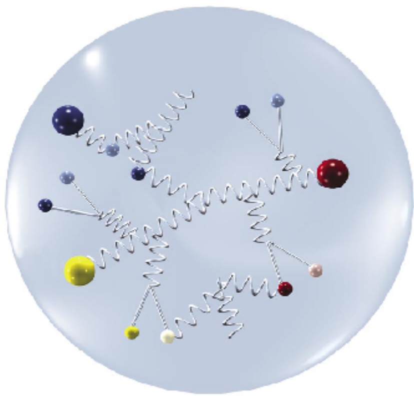
QCD: proton = $uud + u\bar{u} + d\bar{d} + s\bar{s} + \ldots$

The proton sea has a non-trivial structure: $\bar{u} \neq \bar{d}$

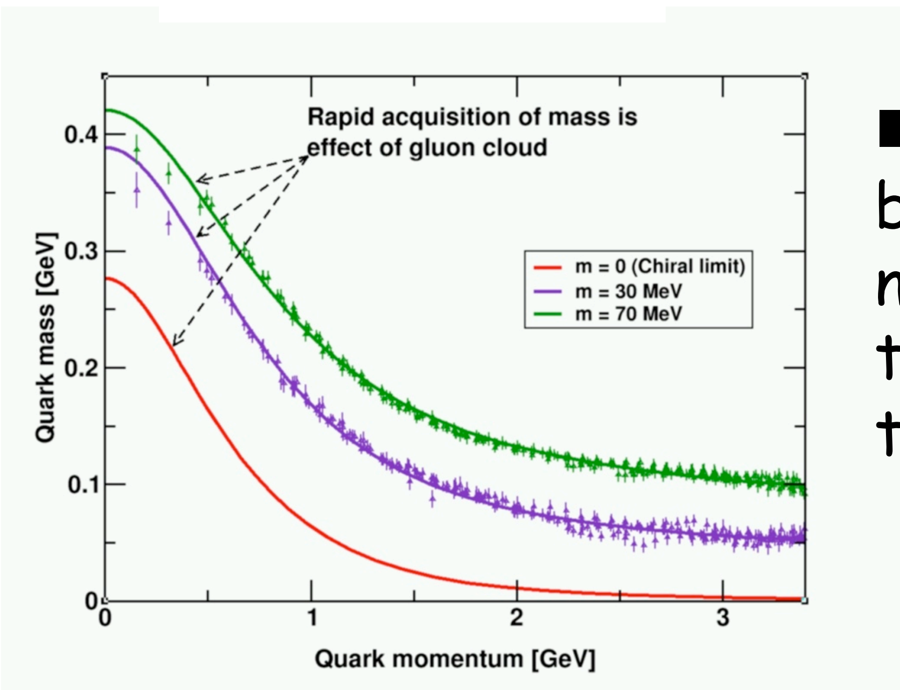


The proton is **far more** than just its up + up + down (valence) quark structure

QCD and the Origin of Mass



- 99% of the proton's mass/energy is due to the self-generating gluon field
  - Higgs mechanism has almost no role here.



- The similarity of mass between the proton and neutron arises from the fact that the gluon dynamics are the same
  - Quarks contribute almost nothing.

The Science of an EIC

Nuclear Science Goal: How do we understand the visible matter in our universe in terms of the fundamental quarks and gluons of QCD?

Overarching EIC Goal: Explore and Understand QCD

Three Major Science Questions for an EIC (from NSAC LRP07):

1) What is the internal landscape of the nucleons?
2) What is the role of gluons and gluon self-interactions in nucleons and nuclei?
3) What governs the transition of quarks and gluons into pions and nucleons?

Or, Elevator-Talk EIC science goals:

- Map the spin and spatial structure of quarks and gluons in nucleons
  (show the nucleon structure picture of the day…)
- Discover the collective effects of gluons in atomic nuclei
  (without gluons there are no protons, no neutrons, no atomic nuclei)
- Understand the emergence of hadronic matter from quarks and gluons
  (how *does* $M = E/c^2$ work to create pions and nucleons?)

+ Hunting for the unseen forces of the universe?

Why an Electron-Ion Collider?

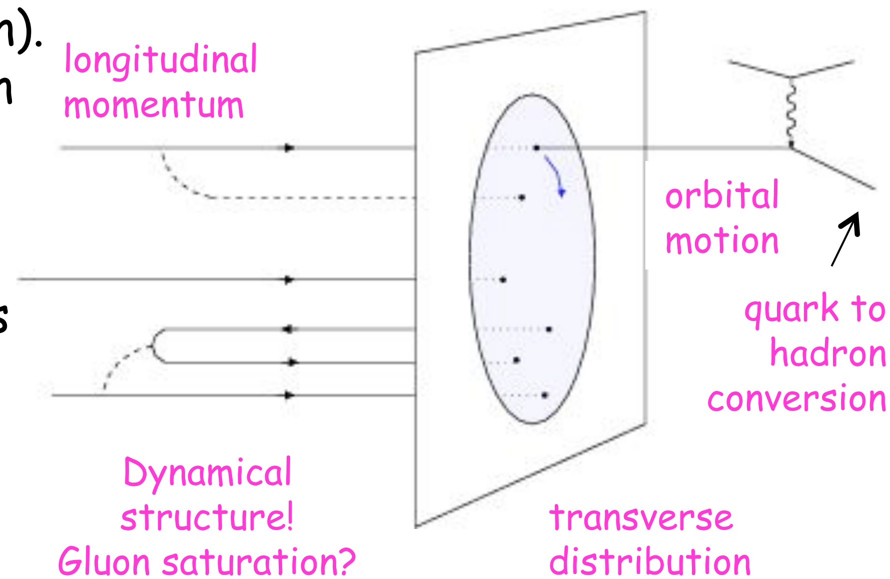
- Longitudinal and Transverse Spin Physics!
  - 70+% polarization of beam and target **without dilution**
  - **transverse** polarization also **70%**!
- Detection of fragments far easier in collider environment!
  - fixed-target experiments boosted to forward hemisphere
  - no fixed-target material to stop target fragments
  - access to neutron structure w. deuteron beams (@ $p_m = 0$!)
- Easier road to do physics at high CM energies!
  - $E_{cm}^2 = s = 4E_1E_2$ for colliders, vs. $s = 2ME$ for fixed-target
    → 4 GeV electrons on 12 GeV protons ~ 100 GeV fixed-target
  - Easier to produce many J/Ψ's, high-p_T pairs, etc.
  - Easier to establish good beam quality in collider mode

Longitudinal polarization FOM

Target	$f_{dilution, fixed\_target}$	P_{fixed_target}	$f^2P^2_{fixed\_target}$	$f^2P^2_{EIC}$
p	0.2	0.8	0.03	**0.5**
d	0.4	0.5	0.04	**0.5**

Why a New-Generation EIC? Why not HERA?

- Obtain detailed differential **transverse quark and gluon images**
  (derived directly from the t dependence with good t resolution!)
  - Gluon size from J/Ψ and ϕ electroproduction
  - Singlet quark size from deeply virtual compton scattering (DVCS)
  - Strange and non-strange (sea) quark size from π and K production
- Determine the **spin-flavor decomposition of the light-quark sea**
- Constrain the **orbital motions** of quarks & anti-quarks of different flavor
  - The difference between π^+, π^-, and K^+ asymmetries reveals the orbits
- Map both the **gluon momentum distributions of nuclei** (F_2 & F_L measurements) and the **transverse spatial distributions of gluons on nuclei** (coherent DVCS & J/Ψ production).
- At high gluon density, the recombination of gluons should compete with gluon splitting, rendering **gluon saturation**. Can we reach such state of saturation?
- Explore the interaction of color charges with matter and understand the **conversion of quarks and gluons to hadrons** through fragmentation and breakup.



The Science of an EIC

Or, Elevator-Talk EIC science goals:

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(show the nucleon structure picture of the day…)

Discover the collective effects of gluons in atomic nuclei

(without gluons there are no protons, no neutrons, no atomic nuclei)

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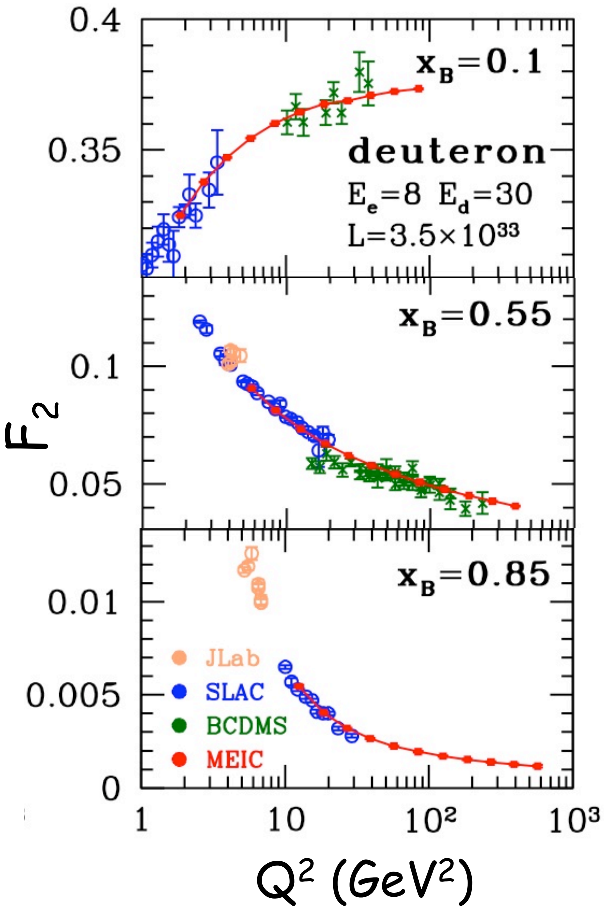
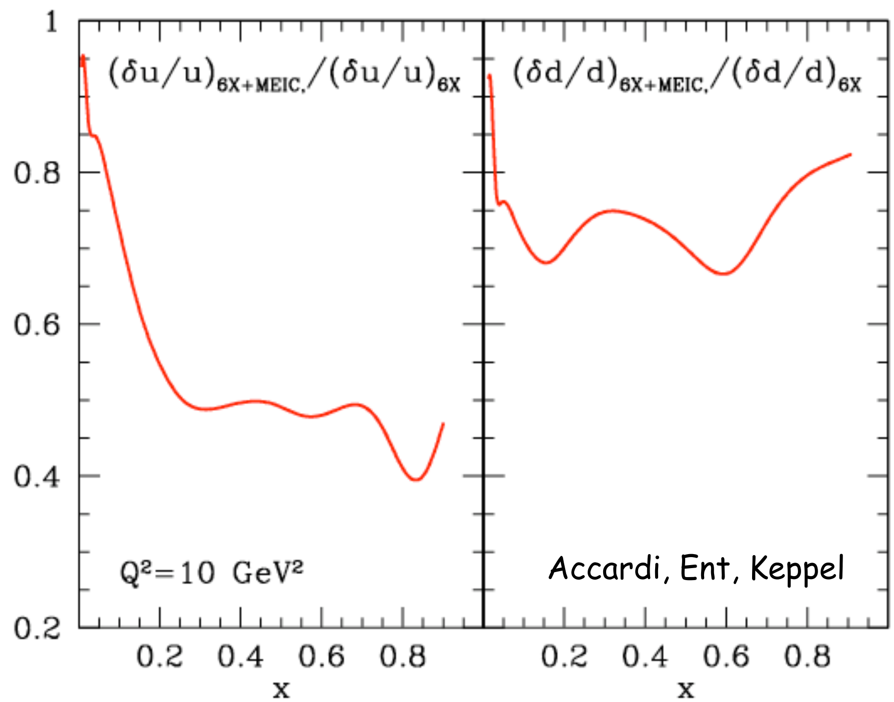
F_2^p & F_2^d @ high x still needed from EIC



- s = 2000
- One year of running (26 weeks) at 50% efficiency, or **35 fb^{-1}**

- *Similar improvement in F_2^p at large x*
- *F_2^n tagging measurements relatively straightforward in EIC designs*
- *EIC will have excellent kinematics to further measure/constrain n/p at large x!*



Sensible reduction in PDF error, likely larger reduction if also energy scan

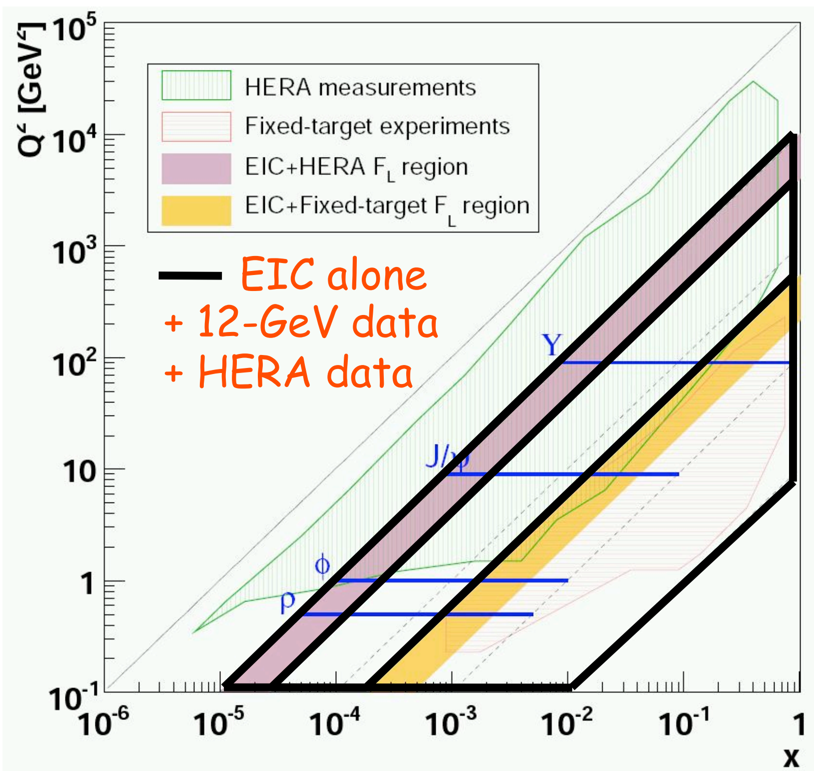
F_L at EIC: Measuring the Glue Directly

Longitudinal Structure Function F_L: Highly sensitive to gluon distributions!

- Experimentally can be determined directly IF VARIABLE ENERGIES!

$$\int_0^1 dx F_L(x,Q^2) = \frac{\alpha_s(Q^2)}{4\pi}\left(\frac{4}{9}\int_0^1 dx F_2(x,Q^2) + \frac{2\sum e_q^2}{12}\int_0^1 dx\, x G(x,Q^2)\right)$$

known



EIC offers complementary measurements of the Gluon distribution $G(x,Q^2)$:

- inelastic vector meson production (e.g. J/ψ)
- diffractive vector meson production ~ $[G(x,Q^2)]^2$

→ Revolutionary access to transverse imaging of gluons

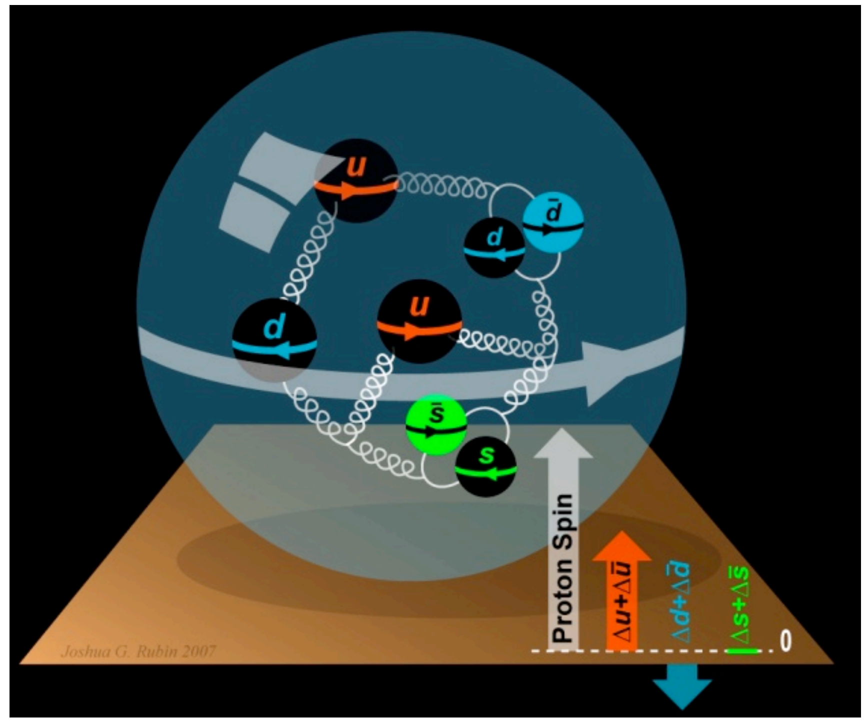
Where does the spin of the proton originate?

(let alone other hadrons…)

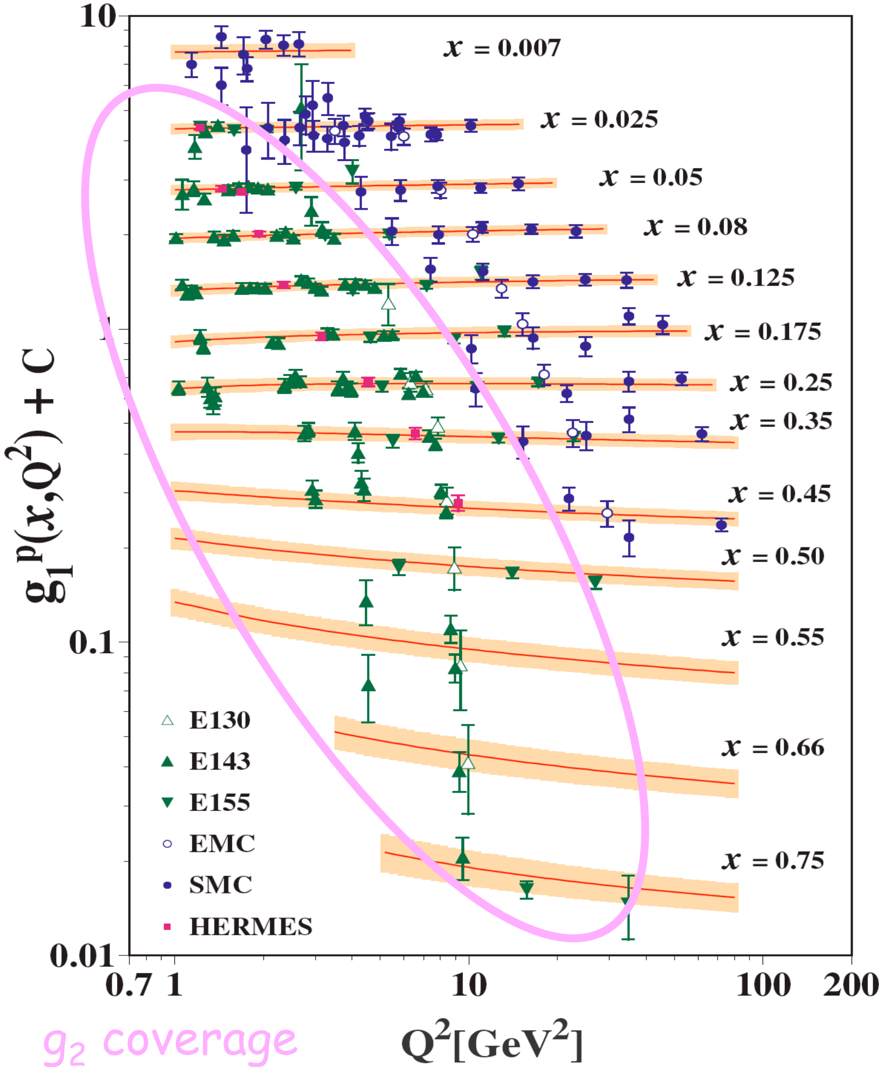
The Standard Model tells us that spin arises from the spins and orbital angular momentum of the quarks and gluons:

$$\boxed{\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L}$$

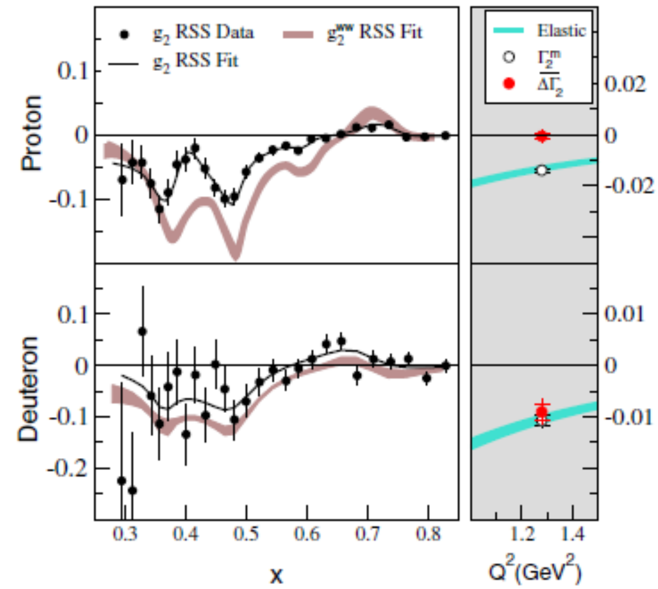
- Experiment: $\Delta\Sigma \approx 0.3$
- Gluons contribute to much of the mass and ≈ half of the momentum of the proton, but…
- … recent results (RHIC-Spin, COMPASS@CERN) indicate that their contribution to the proton spin is small: $\Delta G < 0.1$? (*but only in small range of x…*)
- L_u, L_d, L_g?

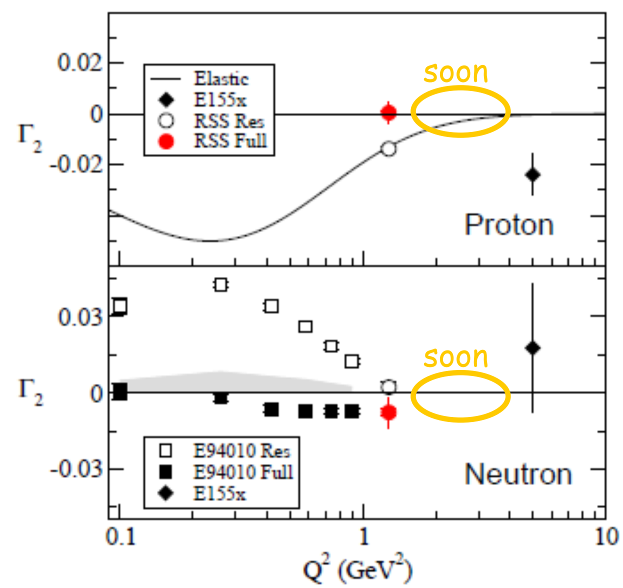


World Data on g_1^p



World Data on $g_2^{p\&n}$

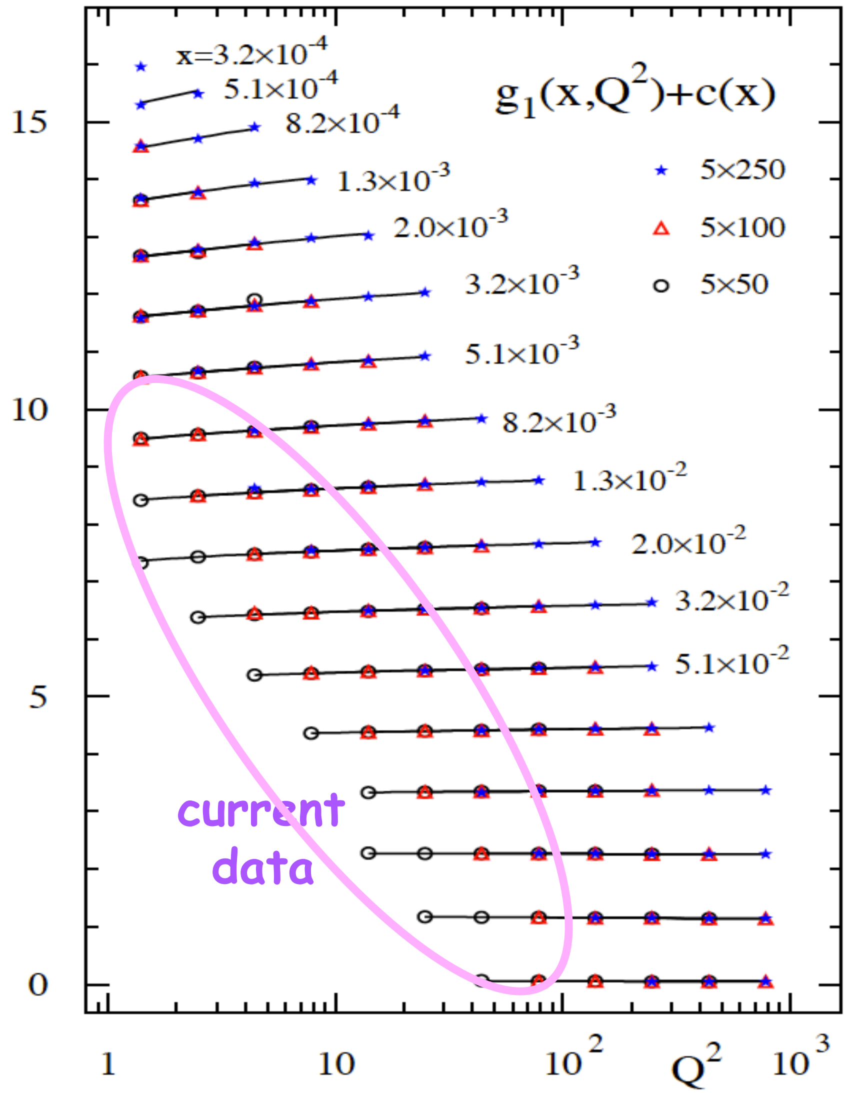




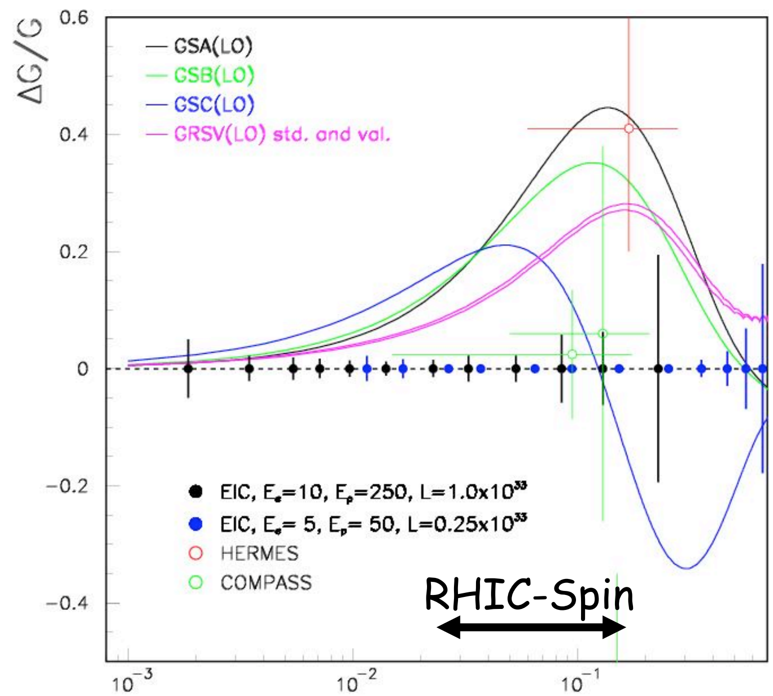
→ 30% of proton spin carried by quark spin

Projected g_1^p Landscape of the EIC

Aschenauer, Burton



Access to $\Delta g/g$ is possible from the g_1^p measurements through the QCD evolution, or from open charm (D^0) production (see below), or from di-jet measurements.



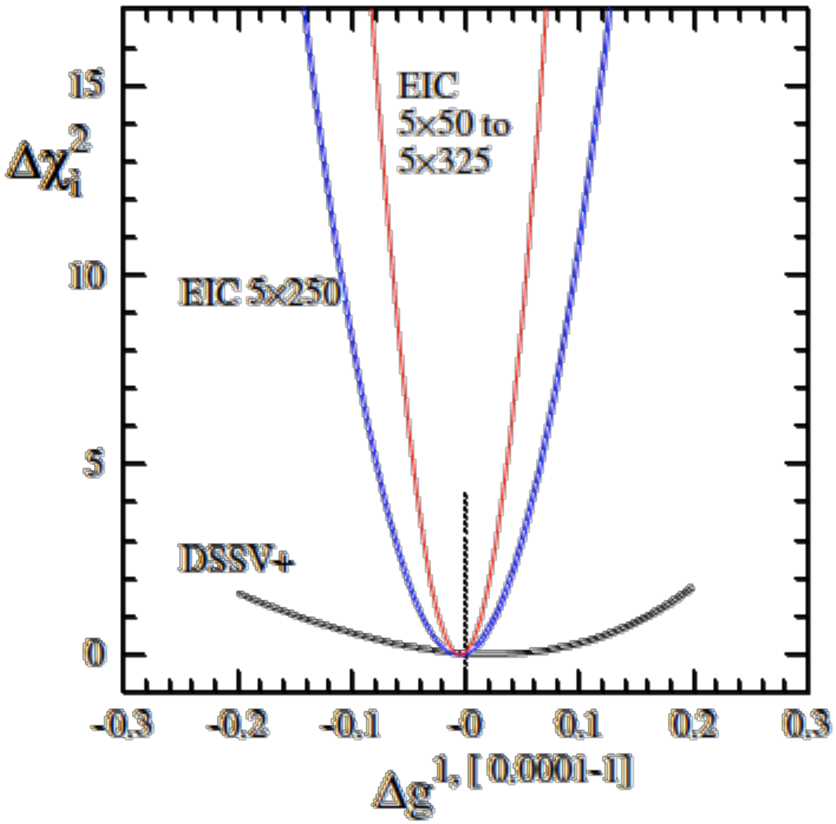
Bruell, Ent

Similar for g_2^p (and g_2^n)!

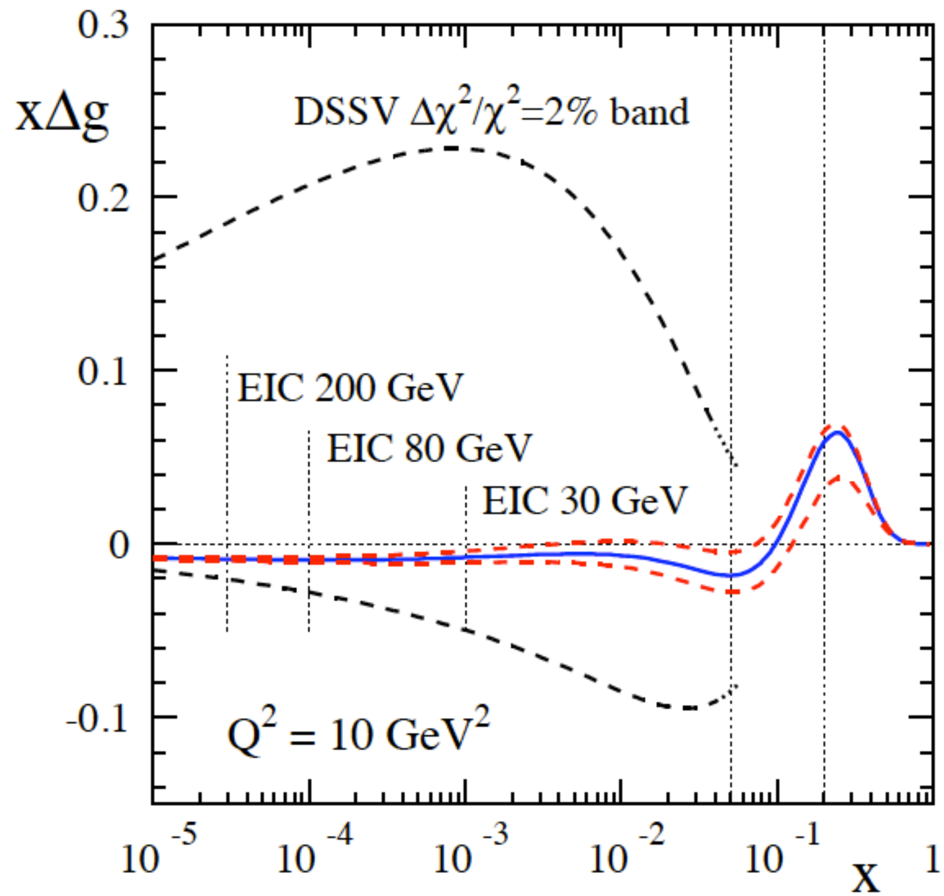
What can be achieved for Δg?

how effective are scaling violations at the EIC…

Sassot, Stratmann



what about the uncertainties on the x-shape …



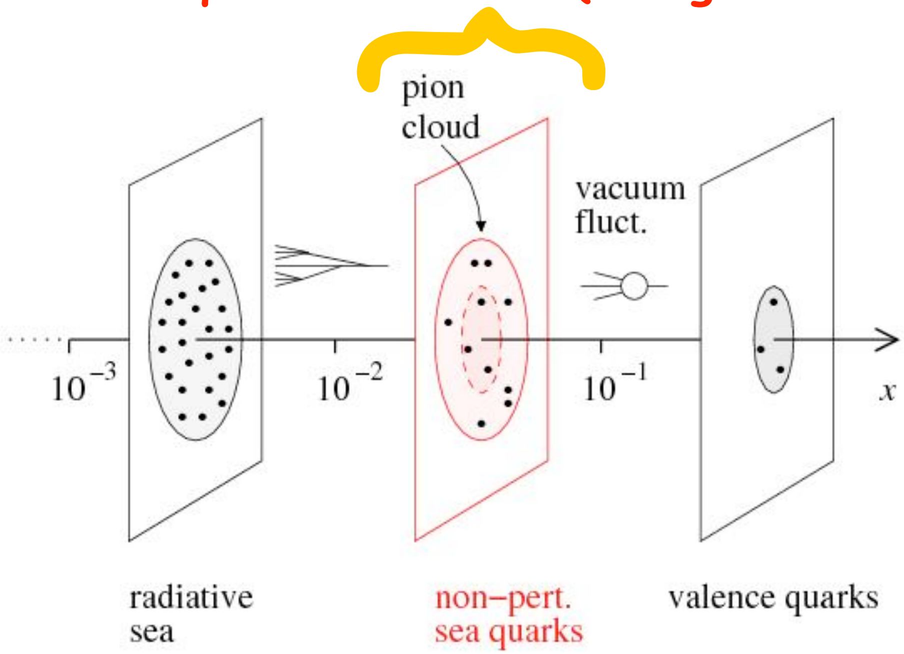
DSSV+ includes also latest COMPASS (SI)DIS data

(no impact on DSSV Δg)

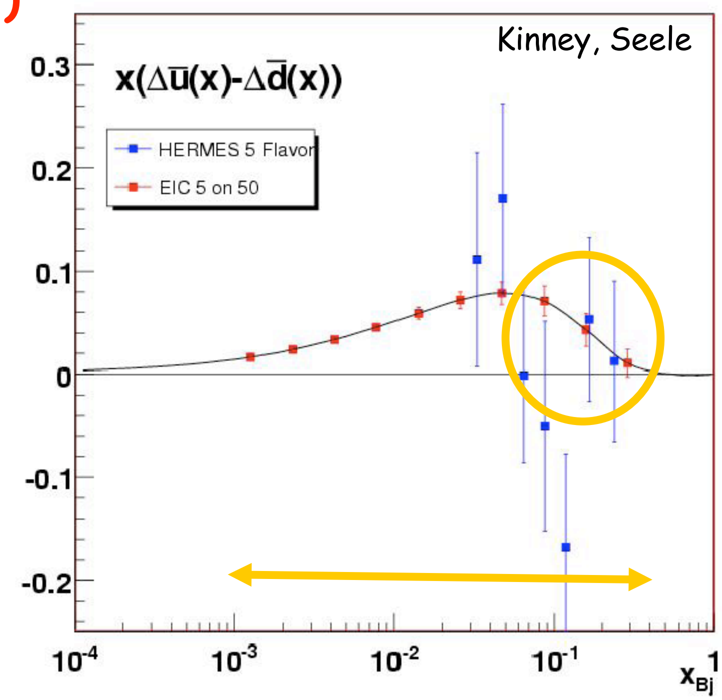
Sea Quark Polarization

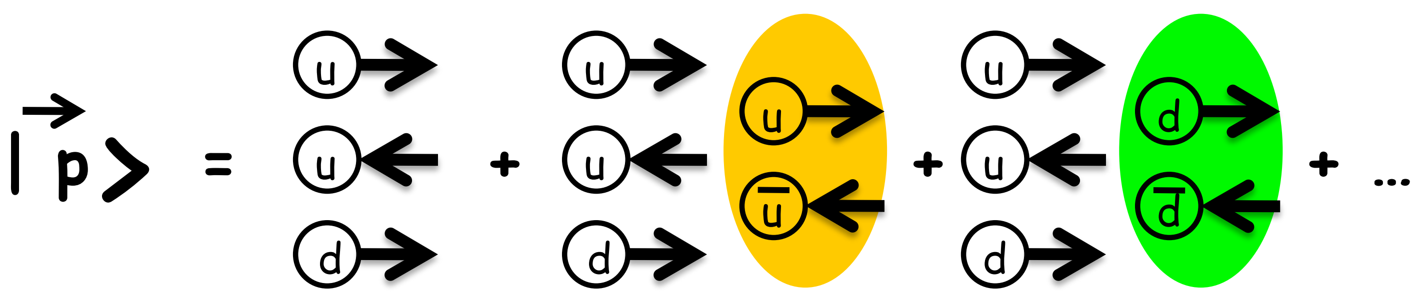
- Spin-Flavor Decomposition of the Light Quark Sea

  Access requires s ~ 1000 (and good luminosity)



100 days, L $=10^{33}$, s = 1000





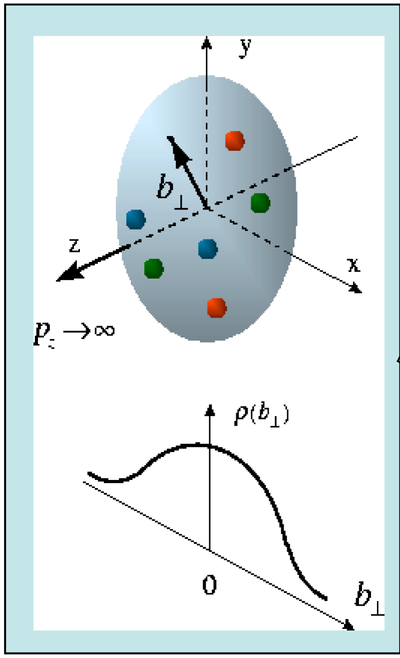
Many models predict

$\Delta\bar{u} > 0$, $\Delta\bar{d} < 0$

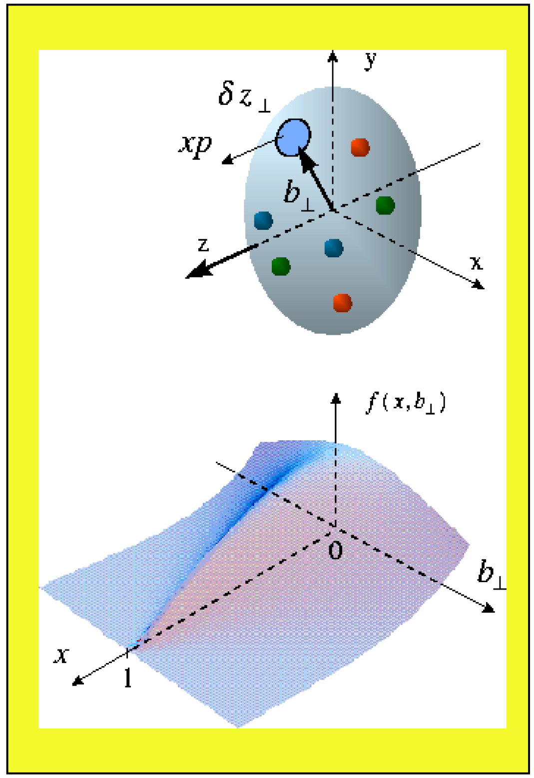
Beyond form factors and quark distributions –

Generalized Parton and Transverse Momentum Distributions

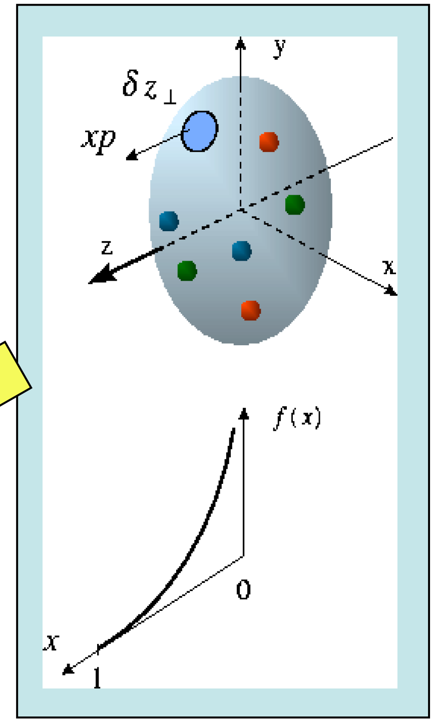
X. Ji, D. Mueller, A. Radyushkin (1994-1997)



Proton form factors, transverse charge & current densities



Correlated quark momentum and helicity distributions in transverse space - GPDs



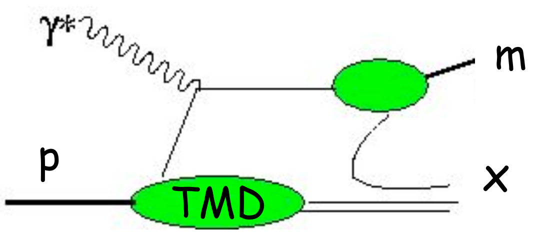
Structure functions, quark longitudinal momentum & helicity distributions

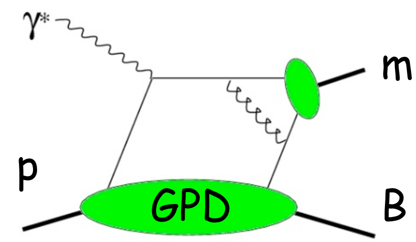
2000's

Extend longitudinal quark momentum & helicity distributions to transverse momentum distributions - TMDs

Towards a "3D" spin-flavor landscape

$W^u(x,\mathbf{k},\mathbf{r})$ (Wigner Function)





d^3r

d^2k_T

Link to Orbital Momentum

$TMD^u(x,k_T)$

$f_1, g_1, f_{1T}^{\perp}, g_{1T}$

$h_1, h_{1T}^{\perp}, h_{1L}^{\perp}, h_1^{\perp}$

$GPD^u(x,\xi,t)$

$H^u, E^u, \tilde{H}^u, \tilde{E}^u$

Link to Orbital Momentum

Want $P_T > \Lambda$ but not too large!

d^2k_T

$\xi = 0, t = 0$

dx

$f_1(x)$

g_1, h_1

$u(x)$

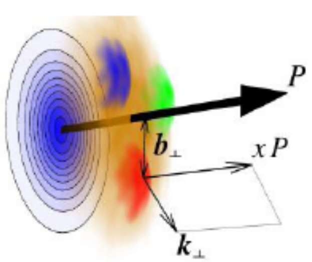
$\Delta u, \delta u$

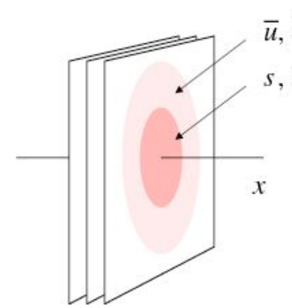
Parton Distributions

$F_1^u(t)$

F_2^u, G_A^u, G_P^u

Form Factors

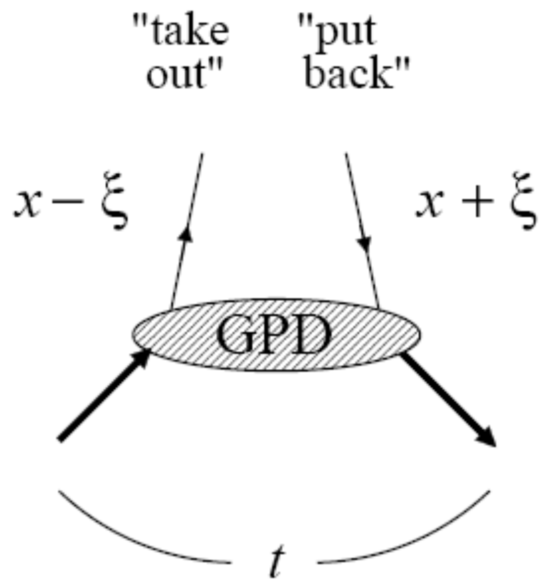




Transverse Quark & Gluon Imaging

Deep exclusive measurements in ep/eA with an EIC:

diffractive:	transverse gluon imaging	J/ψ, ϕ, ρ^o, γ (DVCS)
non-diffractive:	quark spin/flavor structure	π, K, ρ^+, …



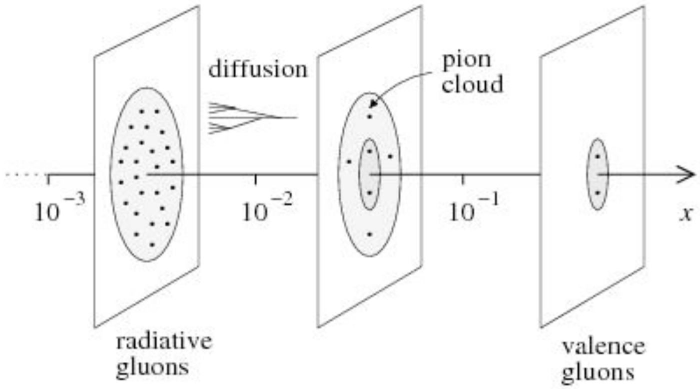
Are gluons uniformly distributed in nuclear matter or are there small clumps of glue? Are gluons & various quark flavors similarly distributed?

(some hints to the contrary)

Describe correlation of longitudinal momentum and transverse position of quarks/gluons →

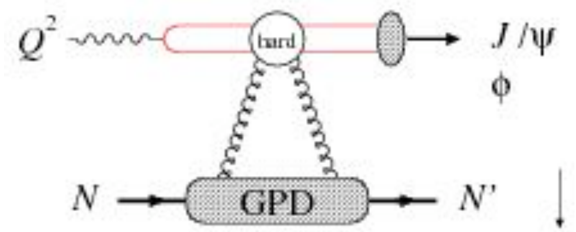
Transverse quark/**gluon** imaging of nucleon ("tomography")

Detailed differential images from nucleon's partonic structure



Weiss, Hyde, Horn

EIC: Gluon size from J/Ψ and φ electroproduction (Q^2 > 10 GeV^2)



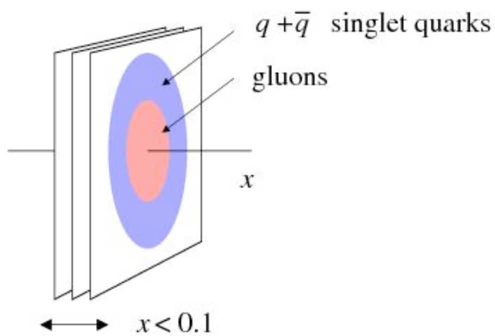
[Transverse distribution derived directly from t dependence]

Hints from HERA:

Area ($q + \bar{q}$) > Area (g)

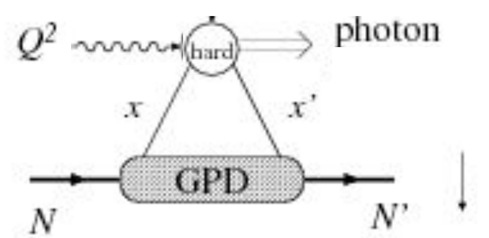
Dynamical models predict difference:

pion cloud, constituent quark picture

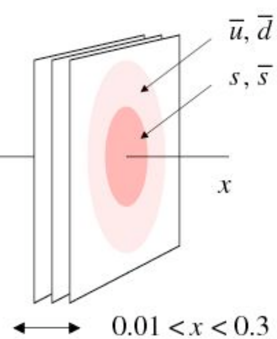


Fazio

EIC: singlet quark size from deeply virtual compton scattering



- Q^2 > 10 GeV^2 for factorization
- Statistics hungry at high Q^2!



Horn

EIC: strange and non-strange (sea) quark size from π and K production

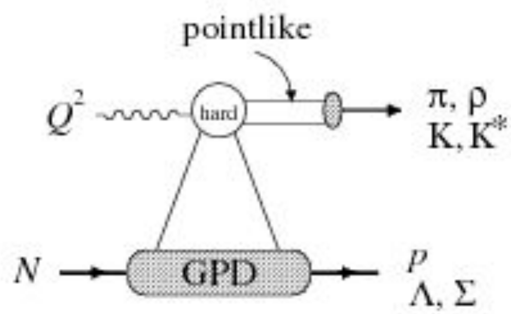
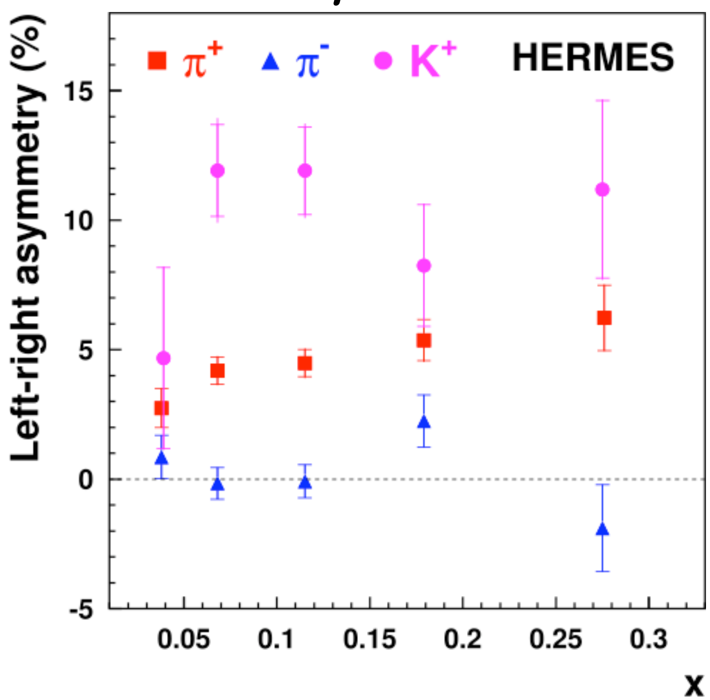


Image the Transverse Momentum of the Quarks

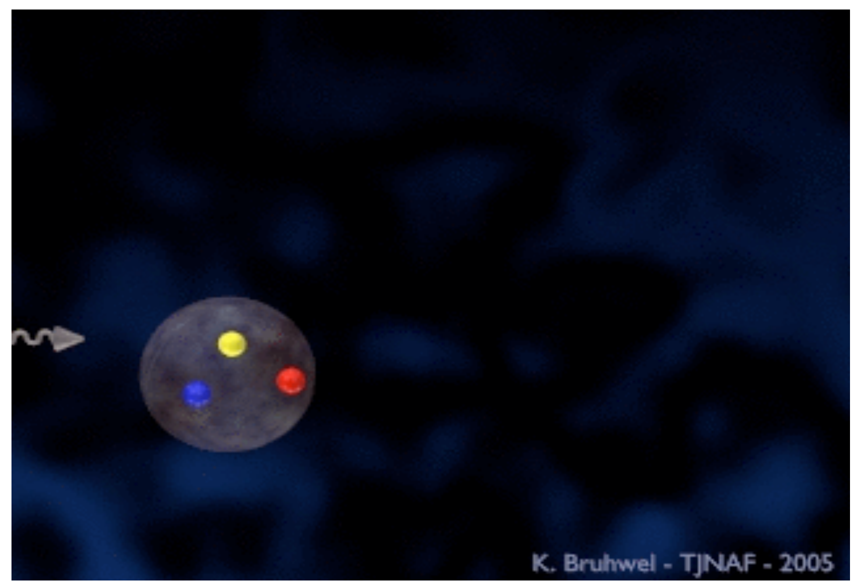
Swing to the left, swing to the right:
A surprise of transverse-spin experiments



The difference between the π^+, π^-, and K^+ asymmetries reveals that quarks and anti-quarks of different flavor are **orbiting in different ways** within the proton.

$$d\sigma^h \sim \Sigma e_q^2 q(x)\ d\sigma_f\ D_f^h(z)$$

Sivers distribution



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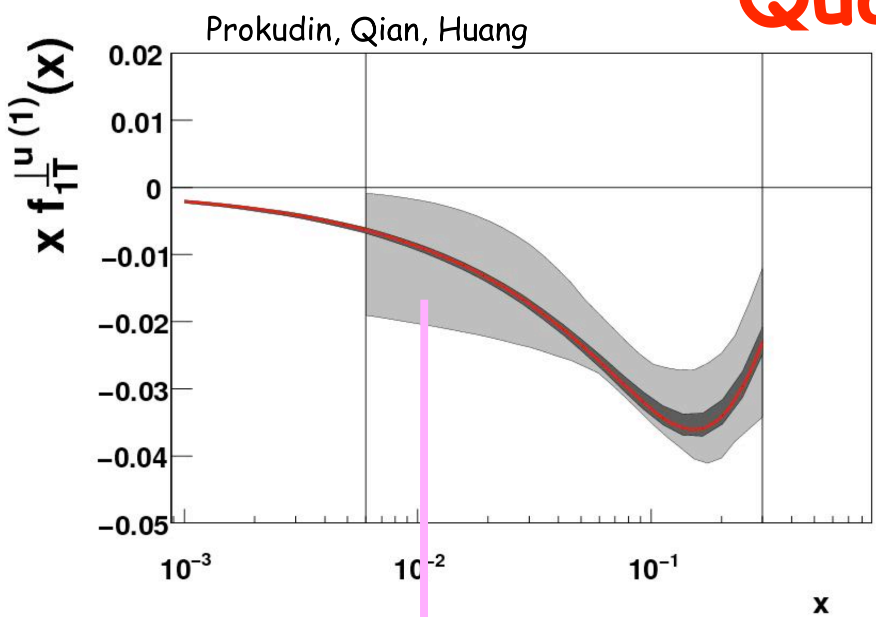
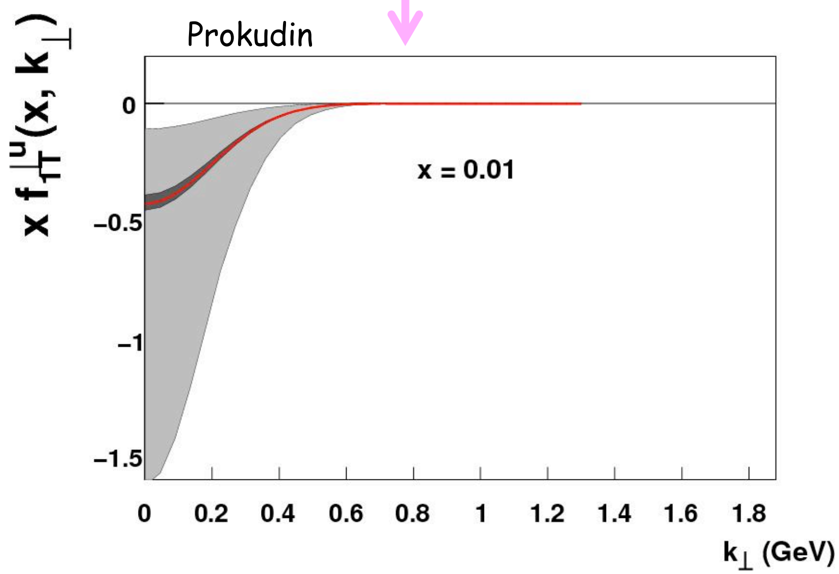




Only a small subset of the (x,Q^2) landscape has been mapped here:

terra incognita

Gray band: present "knowledge"
Red band: EIC (1σ)
(dark gray band: EIC (2σ))

Exact k_T distribution presently essentially unknown!
"Knowledge" of k_T distribution at large k_T is artificial!
(but also perturbative calculable limit at large k_T)

An EIC with good luminosity & high transverse polarization is the optimal tool to to study this!

Summary

The last decade+ has seen tremendous progress in our understanding of the partonic sub-structure of nucleons and nuclei, due to:

- Findings at the US nuclear physics flagship facilities: RHIC and CEBAF
- The surprises found at HERA (H1, ZEUS, HERMES), and now COMPASS/CERN.
- The development of a theory framework allowing for a revolution in our understanding of the inside of hadrons … **GPDs, TMDs, Lattice QCD**
- … hand in hand with the stellar technological advances in polarized beam and parity-quality electron beam delivery.

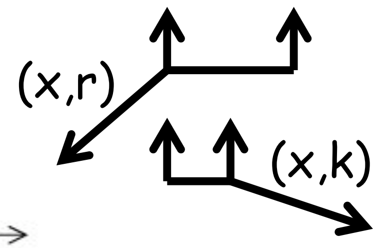
This has led to **new frontiers of nuclear science**:

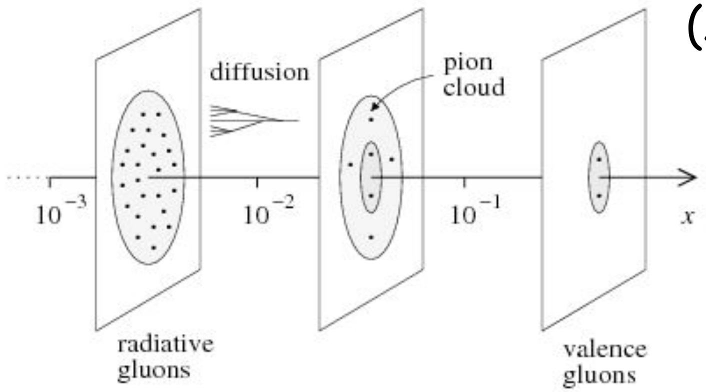
- the possibility to truly **explore and image the nucleon**
- the possibility to understand and build upon **QCD** and study the role of gluons in structure and dynamics
- the unique possibility to study the **interaction of color-charged objects** in vacuum and matter, and their conversion to hadrons
- utilizing precision electroweak studies to complement direct searches for physics **beyond the Standard Model**

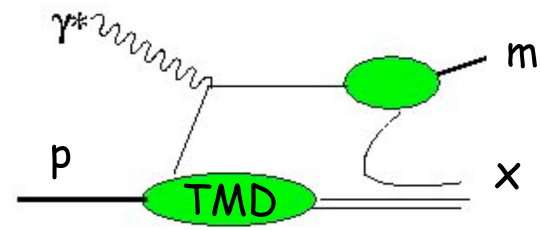
We have **unique opportunities** to make a (future textbook) breakthrough in nucleon structure and QCD dynamics.

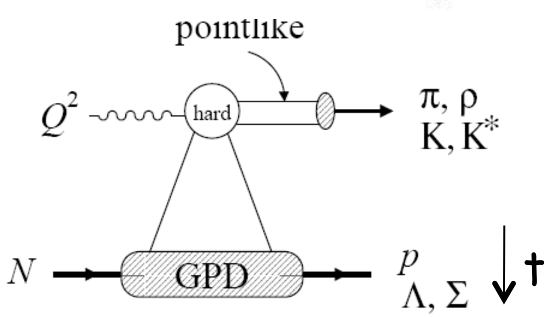
Towards a "3D" spin-flavor landscape

$W^u(x,\mathbf{k},\mathbf{r})$ (Wigner Function)









EIC: Transverse momentum distribution derived directly from semi-inclusive measurements, plus large gain in our knowledge of transverse momentum effects as function of x.

EIC: Transverse spatial distribution derived directly from t dependence:

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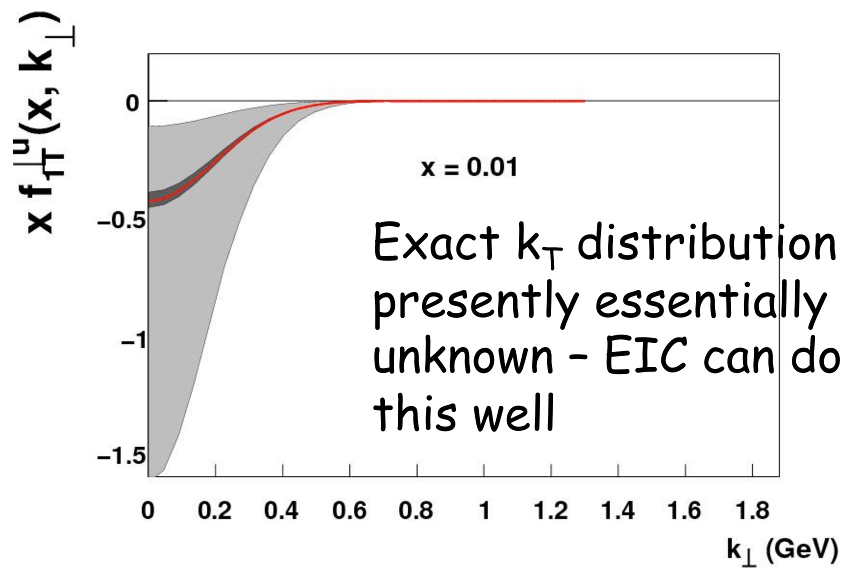
- Singlet quark size from γ
- Strange and non-strange (sea) quark size from π and K production



Exact k_T distribution presently essentially unknown – EIC can do this well

Hints from HERA:

Area $(q + \bar{q})$ > Area (g)

Appendix

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Or, Elevator-Talk EIC science goals:

Map the spin and spatial structure of quarks and gluons in nucleons

(show the nucleon structure picture of the day…)

Discover the collective of gluons in atomic nuclei

(without gluons there are no protons, no neutrons, no atomic nuclei)

Understand the emergence of hadronic matter from quarks and gluons

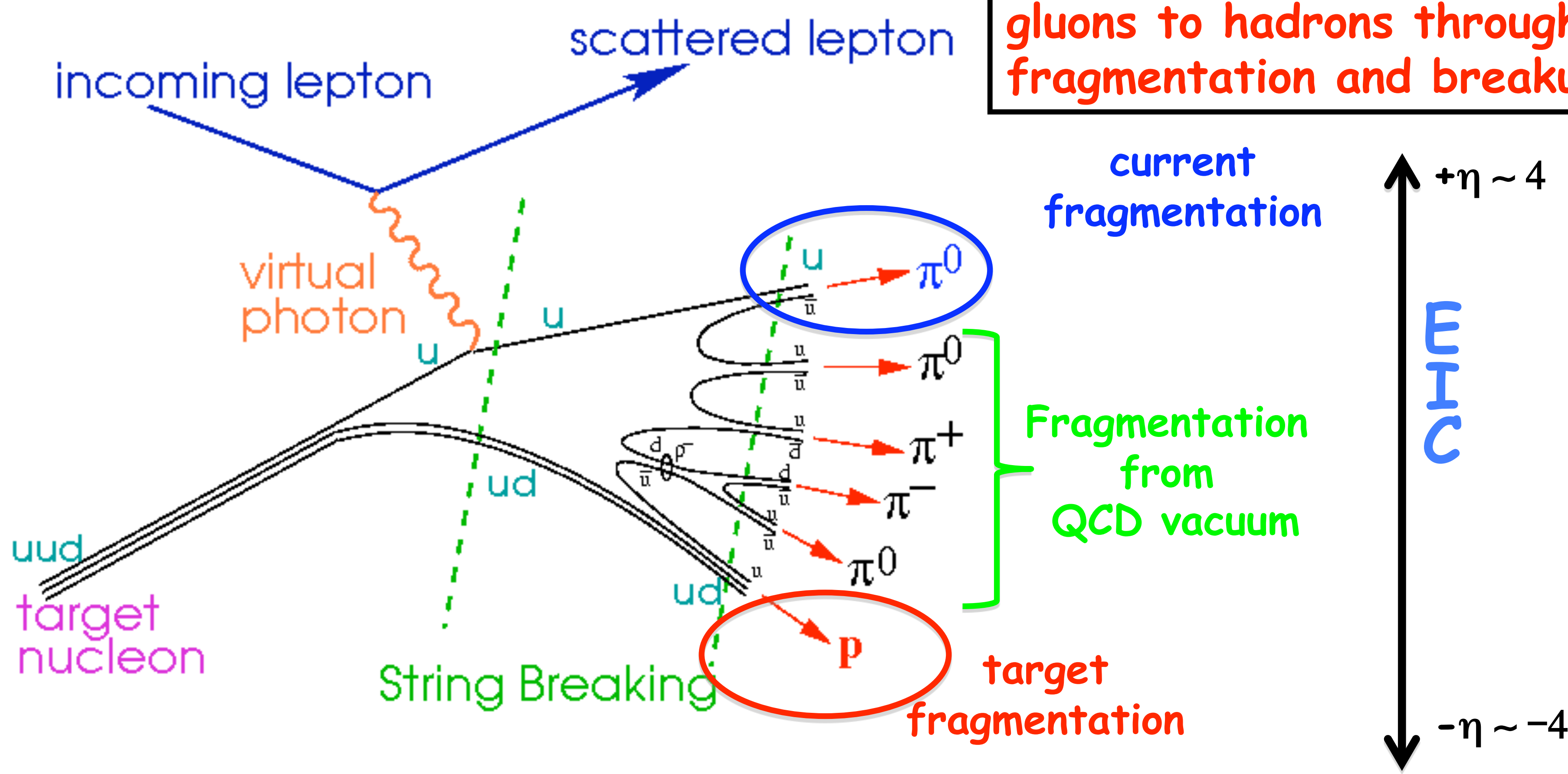
(how *does* $M = E/c^2$ work to create pions and nucleons?)

+ Hunting for the unseen forces of the universe?

Hadronization

- un-integrated parton distributions

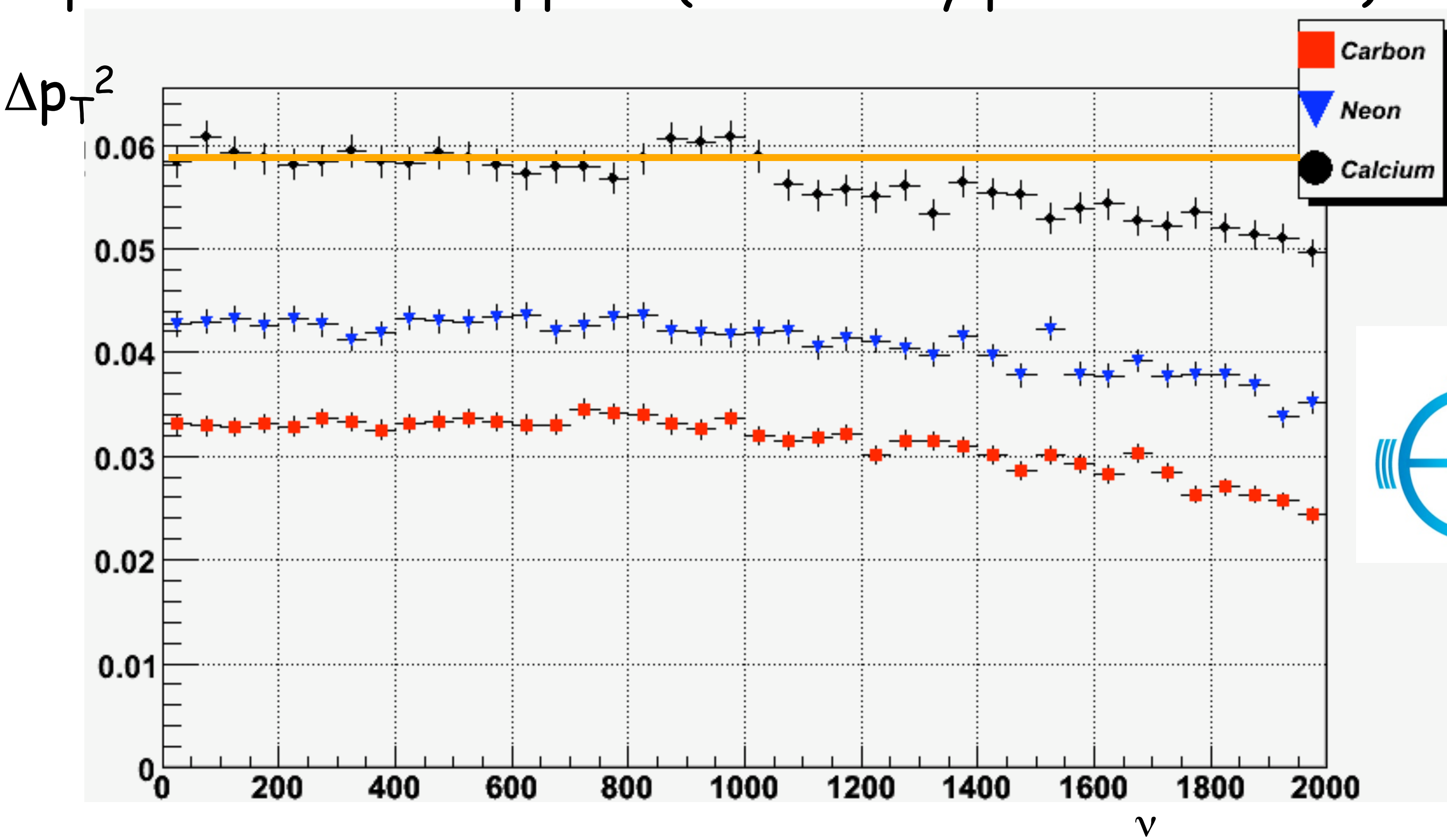
EIC: Understand the conversion of quarks and gluons to hadrons through fragmentation and breakup



EIC: Explore the interaction of color charges with matter

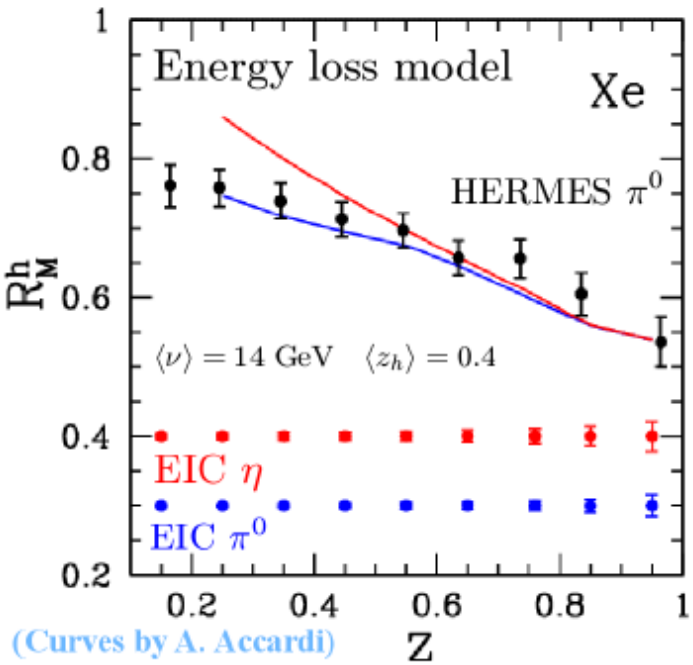
Transverse Momentum Broadening

Δp_T^2 reaches a "plateau" for sufficiently large quark energy, for each nucleus (L is fixed). In the pQCD region, the effect is predicted to disappear (arbitrarily put at ν =1000)

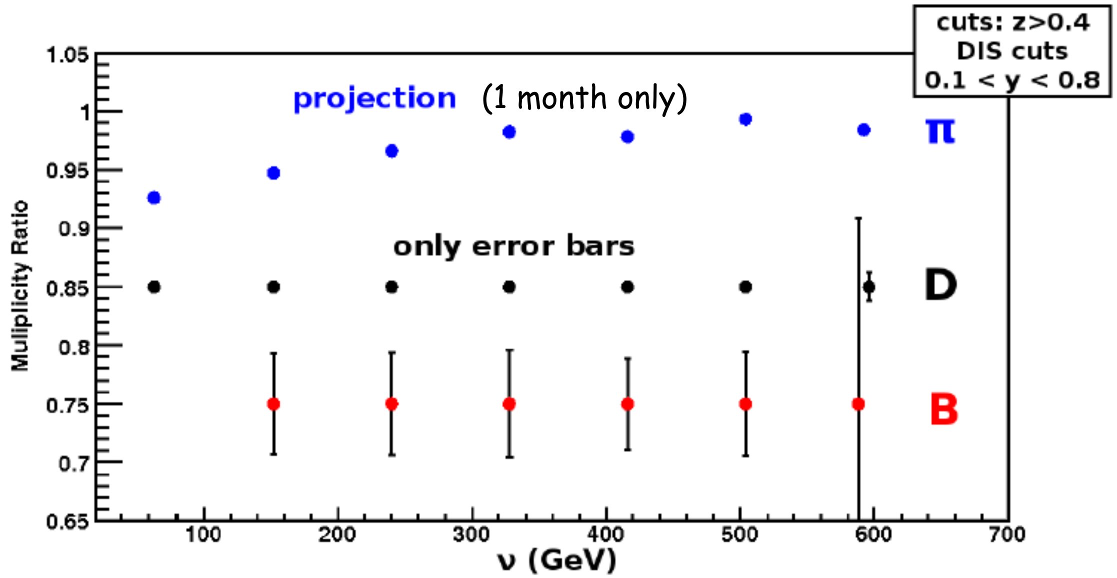


Hadronization

EIC: Explore the interaction of color charges with matter



(Curves by A. Accardi)



EIC: Understand the conversion of quarks and gluons to hadrons through fragmentation and breakup

The Science of an EIC

Or, Elevator-Talk EIC science goals:

Map the spin and spatial structure of quarks and gluons in nucleons

(show the nucleon structure picture of the day…)

Discover the collective of gluons in atomic nuclei

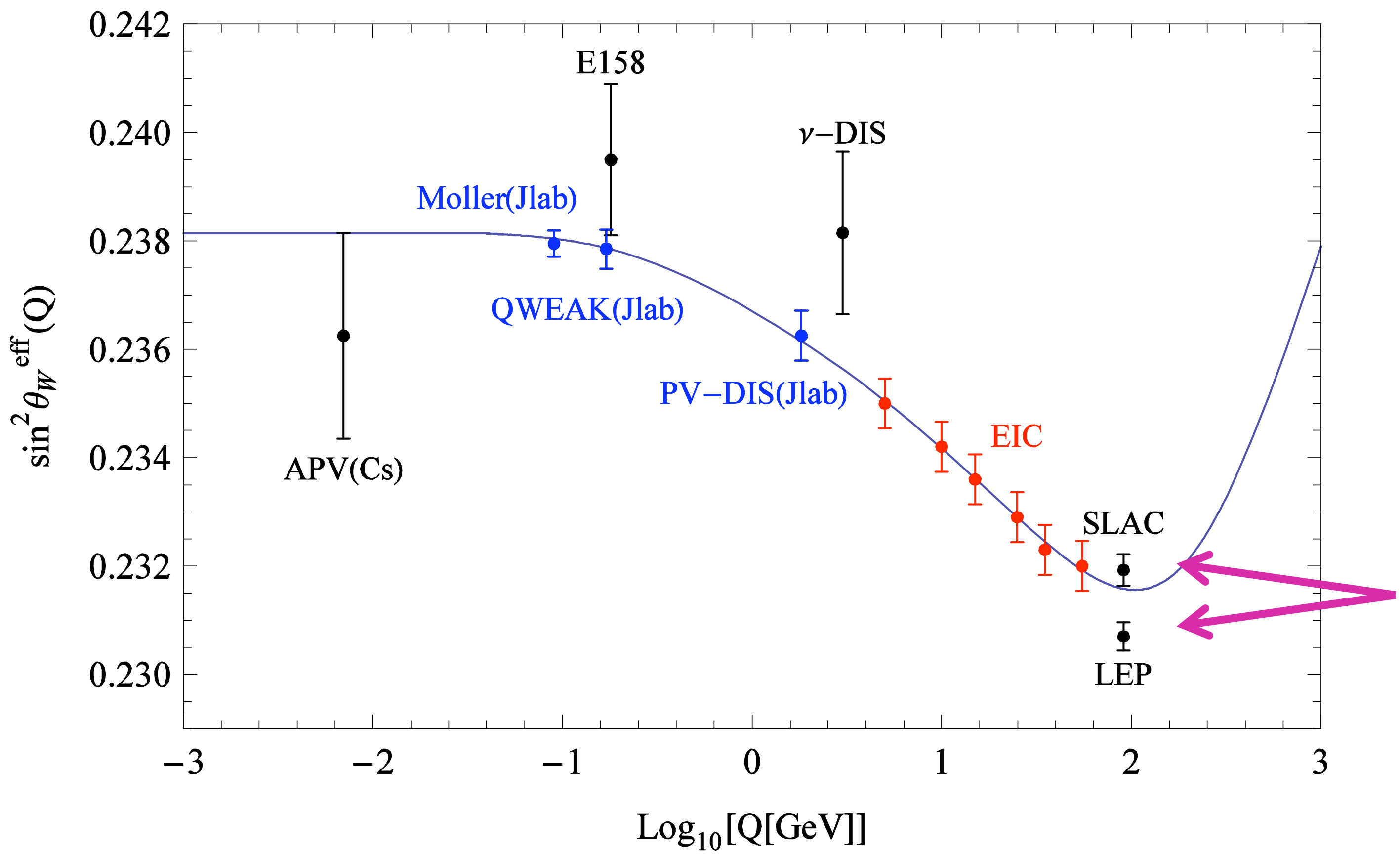
(without gluons there are no protons, no neutrons, no atomic nuclei)

Understand the emergence of hadronic matter from quarks and gluons

(how *does* $M = E/c^2$ work to create pions and nucleons?)

+ Hunting for the unseen forces of the universe?

Completed, planned, and possible EIC measurements



→ EIC allows to probe the electro-weak mixing angle over a wide range of Q

The Electron-Ion Collider

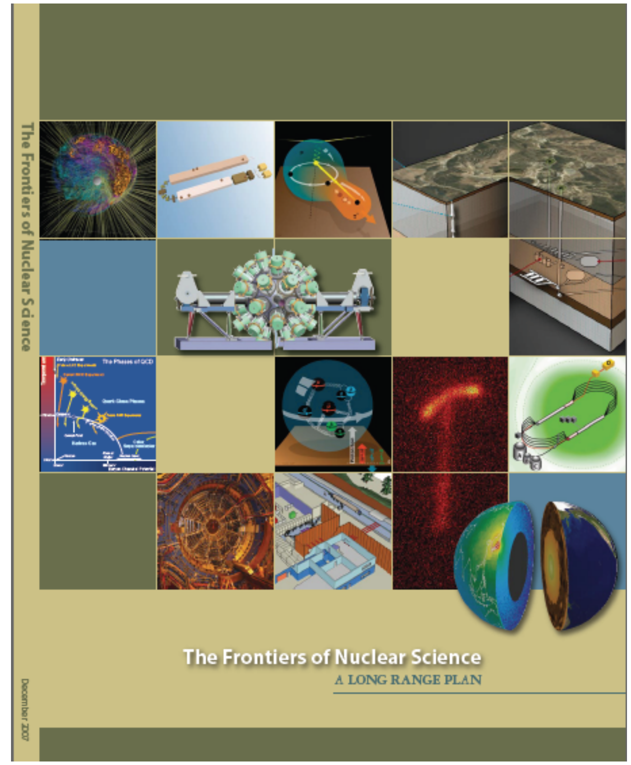
Study the Force Carriers of QCD

The role of Gluons and Sea Quarks

A High-Luminosity Electron Ion Collider

NSAC 2007 Long-Range Plan:

"An **Electron-Ion Collider (EIC)** with **polarized** beams has been **embraced by the U.S. nuclear science community** as embodying the vision for **reaching the next QCD frontier**. EIC would provide unique capabilities for the study of QCD well beyond those available at existing facilities worldwide and complementary to those planned for the next generation of accelerators in Europe and Asia."



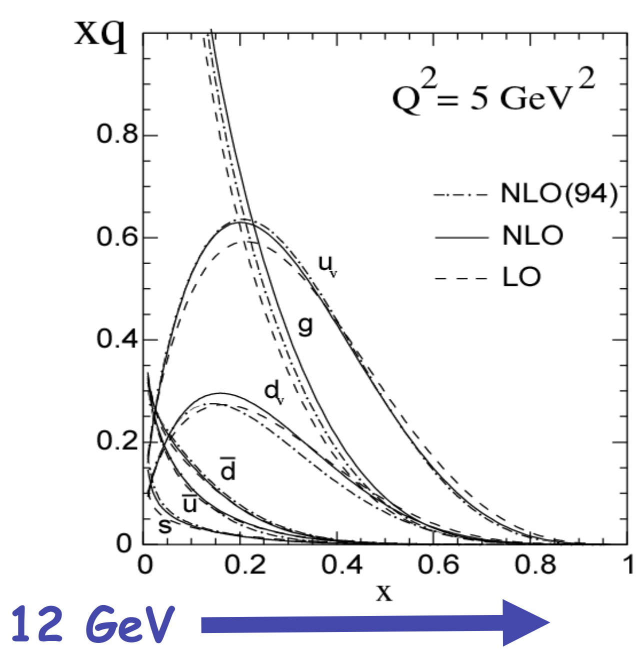
- Base EIC Requirements:
  - range in energies from s = few 100 to s = few 1000 & variable
  - fully-polarized (>70%), longitudinal and transverse
  - ion species up to A = 200 or so
  - high luminosity: about 10^{34} e-nucleons cm^{-2} s^{-1}
  - upgradable to higher energies

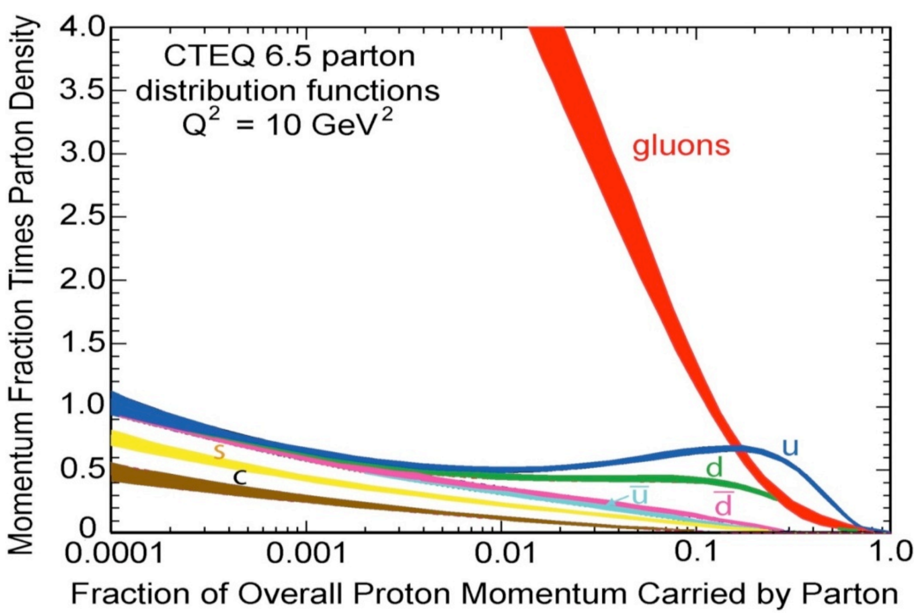
EIC@JLab High-Level Science Overview

• Hadrons in QCD are relativistic many-body systems, with a fluctuating number of elementary quark/gluon constituents and a very rich structure of the wave function.

• With 12 GeV we study mostly the valence quark component, which can be described with methods of nuclear physics (fixed number of particles).

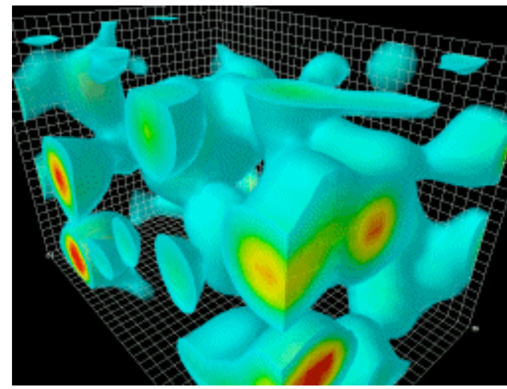
• With an (M)EIC we enter the region where the many-body nature of hadrons, coupling to vacuum excitations, etc., become manifest and the theoretical methods are those of quantum field theory. An EIC aims to study the sea quarks, gluons, and scale (Q^2) dependence.





Gluons and QCD

- QCD is the fundamental theory that describes structure and interactions in nuclear matter.
- Without gluons there are no protons, no neutrons, and no atomic nuclei
- Gluons dominate the structure



um

- Facts:
  - The essential features of QCD (e.g. asymptotic freedom, chiral symmetry breaking, and color confinement) are all driven by the gluons!
  - Unique aspect of QCD is the self interaction of the gluons
  - 99% of mass of the visible universe arises from glue
  - Half of the nucleon momentum is carried by gluons

Progress in Particle and Nuclear Physics 63 (2009) 1–50

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Review

Spin structure of the nucleon—status and recent results

S.E. Kuhn [a,*], J.-P. Chen [b], E. Leader [c]

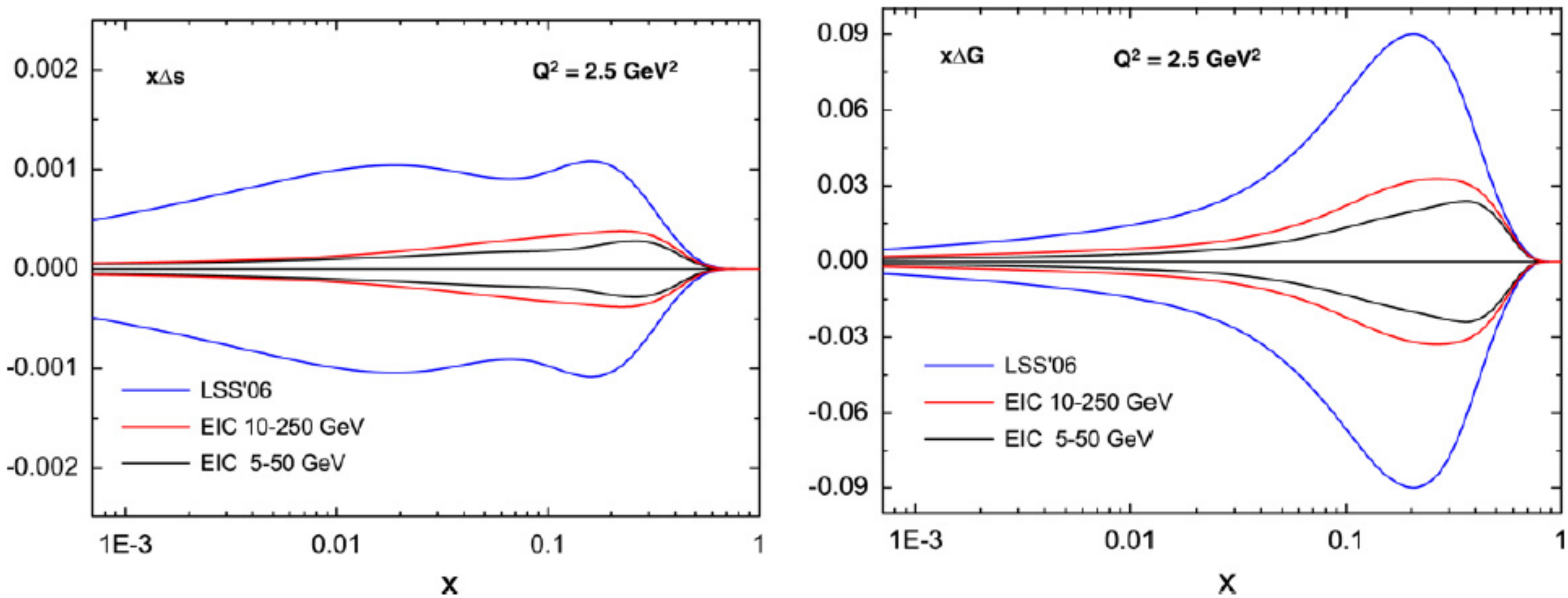
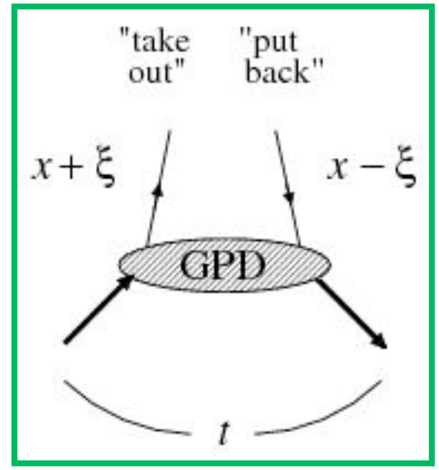


Fig. 46. Impact of two versions of EIC on the s and G uncertainties [217].

A collider of the EIC type would also have a dramatic effect in reducing the uncertainties in the polarized parton densities. This is illustrated in Figs. 45 and 46 where it can be seen that the improvement even at moderate to large x, especially for Δs and ΔG, is remarkable.

What's the use of GPDs?

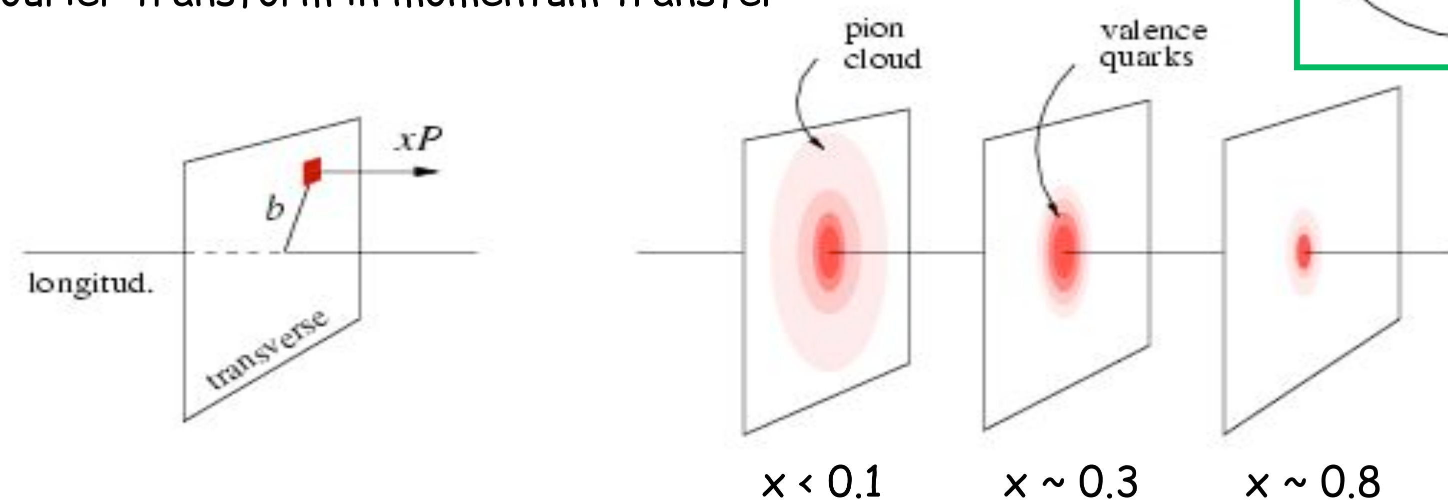
1. Allows for a unified description of form factors and parton distributions



2. Describe correlations of quarks/gluons

3. Allows for Transverse Imaging

Fourier transform in momentum transfer



gives transverse spatial distribution of quark (parton) with momentum fraction x

4. Allows access to quark angular momentum (in model-dependent way)

GPDs and Transverse Gluon Imaging

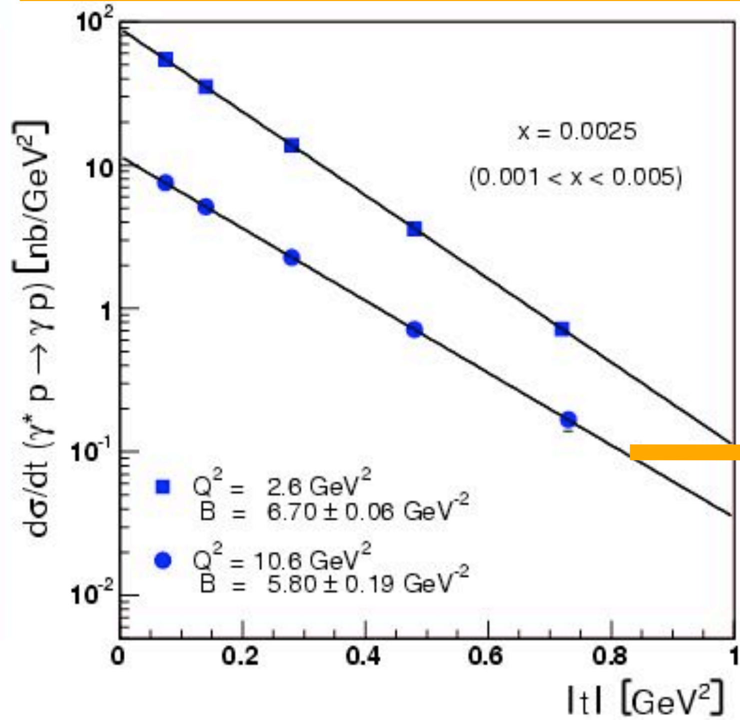
Goal: Transverse gluon imaging of nucleon over wide range of x: 0.001 < x < 0.1

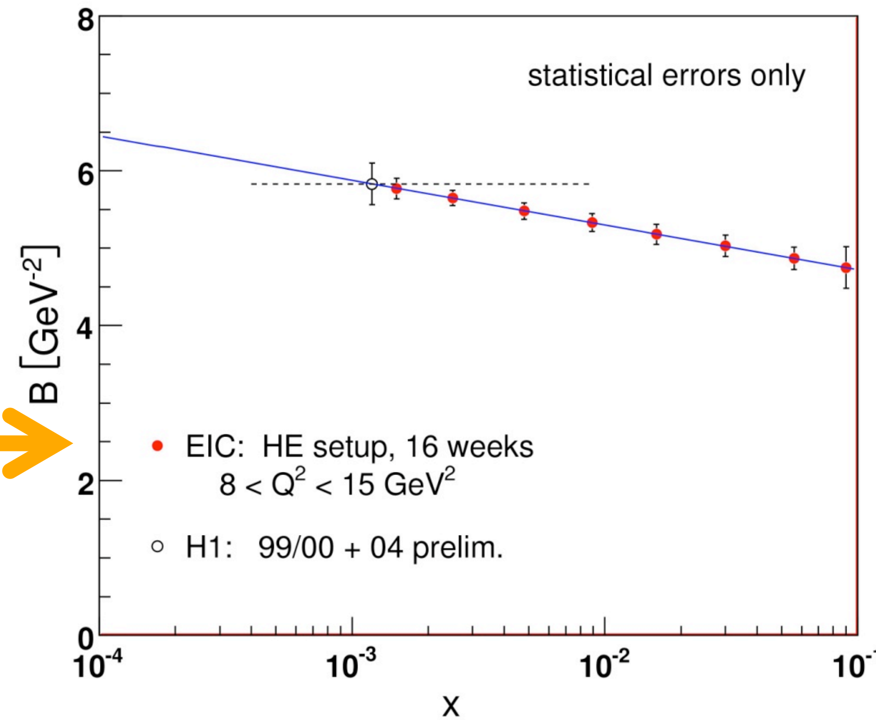
Requires: - Q^2 ~ 10-20 GeV^2 to facilitate interpretation

- Wide Q^2, W^2 (x) range
- <u>luminosity of 10^{33} (or more)</u> to do *differential* measurements in Q^2, W^2, t

Q^2 = 10 GeV^2 projected data

EIC enables gluon imaging!

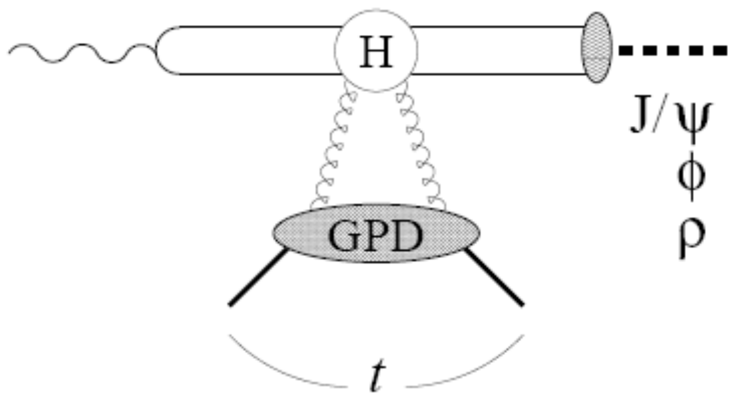




(Andrzej Sandacz)

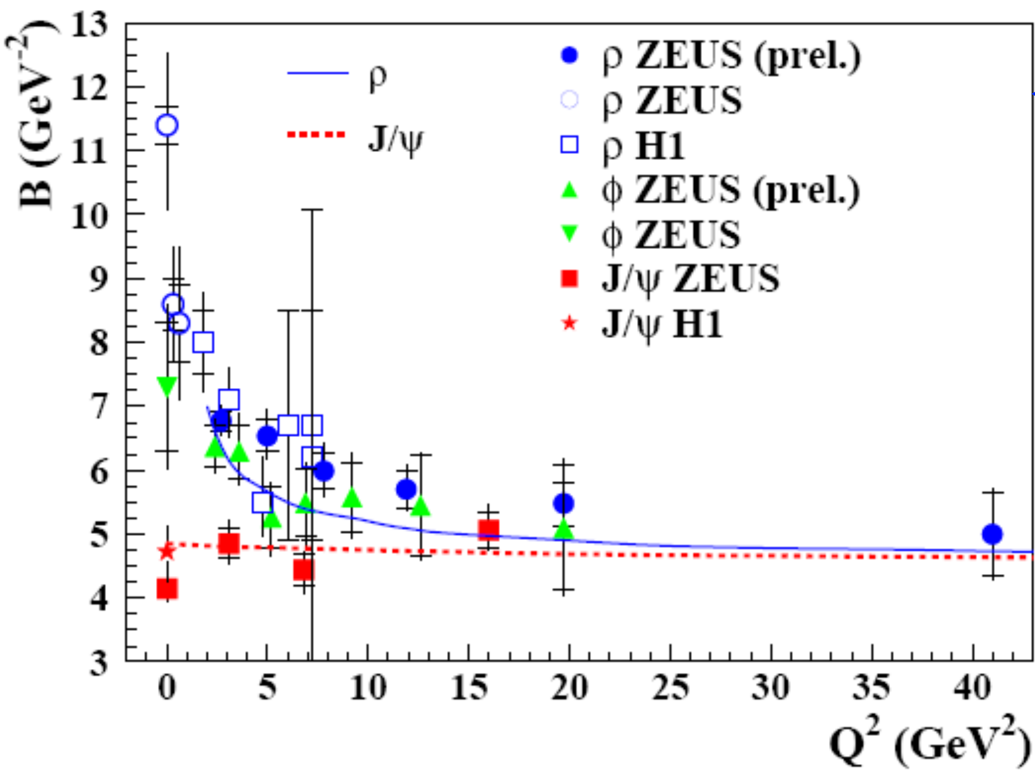
Simultaneous data at other Q^2-values

GPDs and Transverse Gluon Imaging



Two-gluon exchange dominant for J/ψ, φ, ρ production at large energies → **sensitive to gluon distribution squared!**

LO factorization ~ color dipole picture → access to gluon spatial distribution in nuclei: see eA!



Fit with $d\sigma/dt = e^{-Bt}$

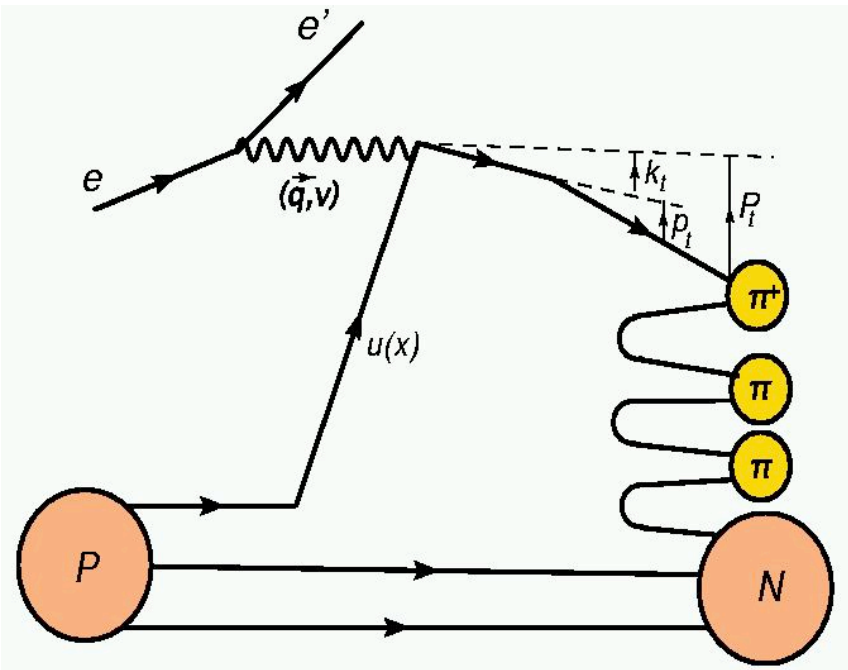
Measurements at DESY of diffractive channels (J/ψ, φ, ρ, γ) confirmed the applicability of QCD factorization:

- t-slopes universal at high Q^2
- flavor relations φ:ρ

Unique access to transverse gluon & quark imaging at EIC!

Transverse Momentum Dependence of Semi-Inclusive Pion Production

- Not much is known about the orbital motion of partons
- Significant net orbital angular momentum of valence quarks implies significant transverse momentum of quarks



Final transverse momentum of the detected pion P_t arises from convolution of the struck quark transverse momentum $\mathbf{k_t}$ with the transverse momentum generated during the fragmentation $\mathbf{p_t}$.

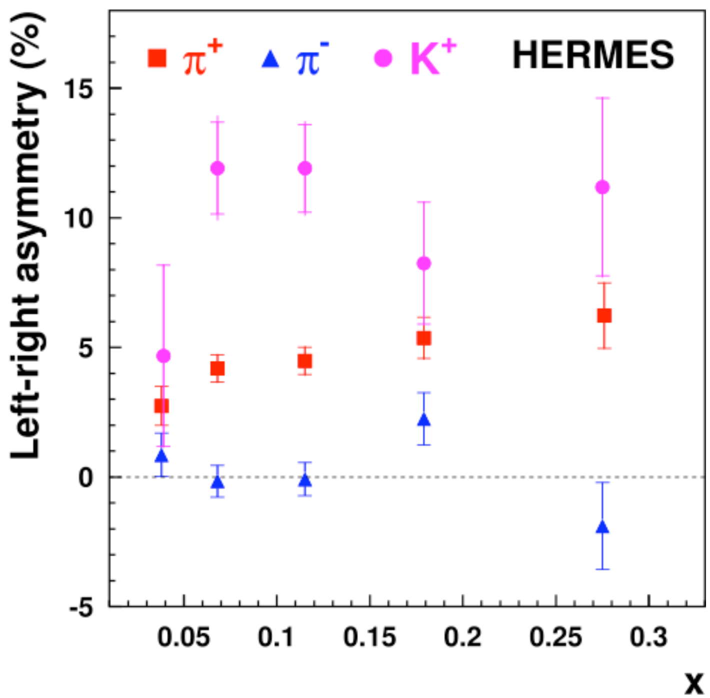
$$P_t = p_t + z\,k_t + O(k_t^2/Q^2)$$

$$z = E_\pi/\nu$$

$p_T \sim \Lambda < 0.5$ GeV optimal for studies as theoretical framework for Semi-Inclusive Deep Inelastic Scattering has been well developed at small transverse momentum *[A. Bacchetta et al., JHEP 0702 (2007) 093].*

Image the Transverse Momentum of the Quarks

Swing to the left, swing to the right:
A surprise of transverse-spin experiments



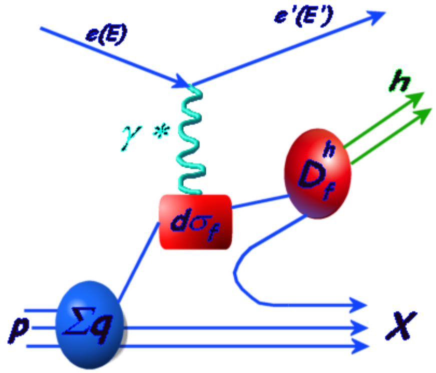
The difference between the π^+, π^-, and K^+ asymmetries reveals that quarks and anti-quarks of different flavor are **orbiting in different ways** within the proton.

An EIC with high transverse polarization is the optimal tool to to study this!

Only a small subset of the (x,Q^2) landscape has been mapped here: terra incognita

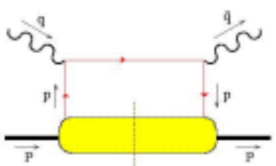
Mechanism for Observed Transverse-Spin Effects

1) Spin-Orbit Effects in the Proton Itself

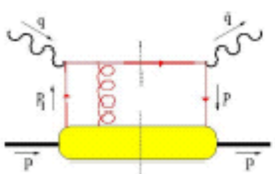


$$d\sigma^h \sim \Sigma e_q^2 q(x)\ d\sigma_f\ D_f^h(z)$$

Sivers distribution

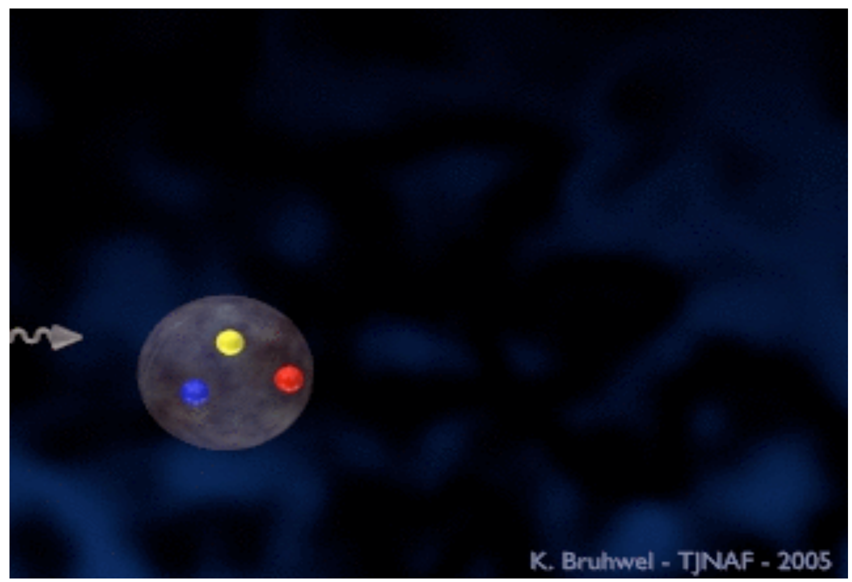


interferes with



(soft gluons)

to establish leading-twist Sivers distribution required



It's there (HERMES)!!!

Single-Spin Asymmetry Projections with Proton

- 11 + 60 GeV

  36 days

  L = 3x10^{34} /cm^2/s

  2x10^{-3} , Q^2<10 GeV^2

  4x10^{-3} , Q^2>10 GeV^2

- 3 + 20 GeV

  36 days

  L = 1x10^{34}/cm^2/s

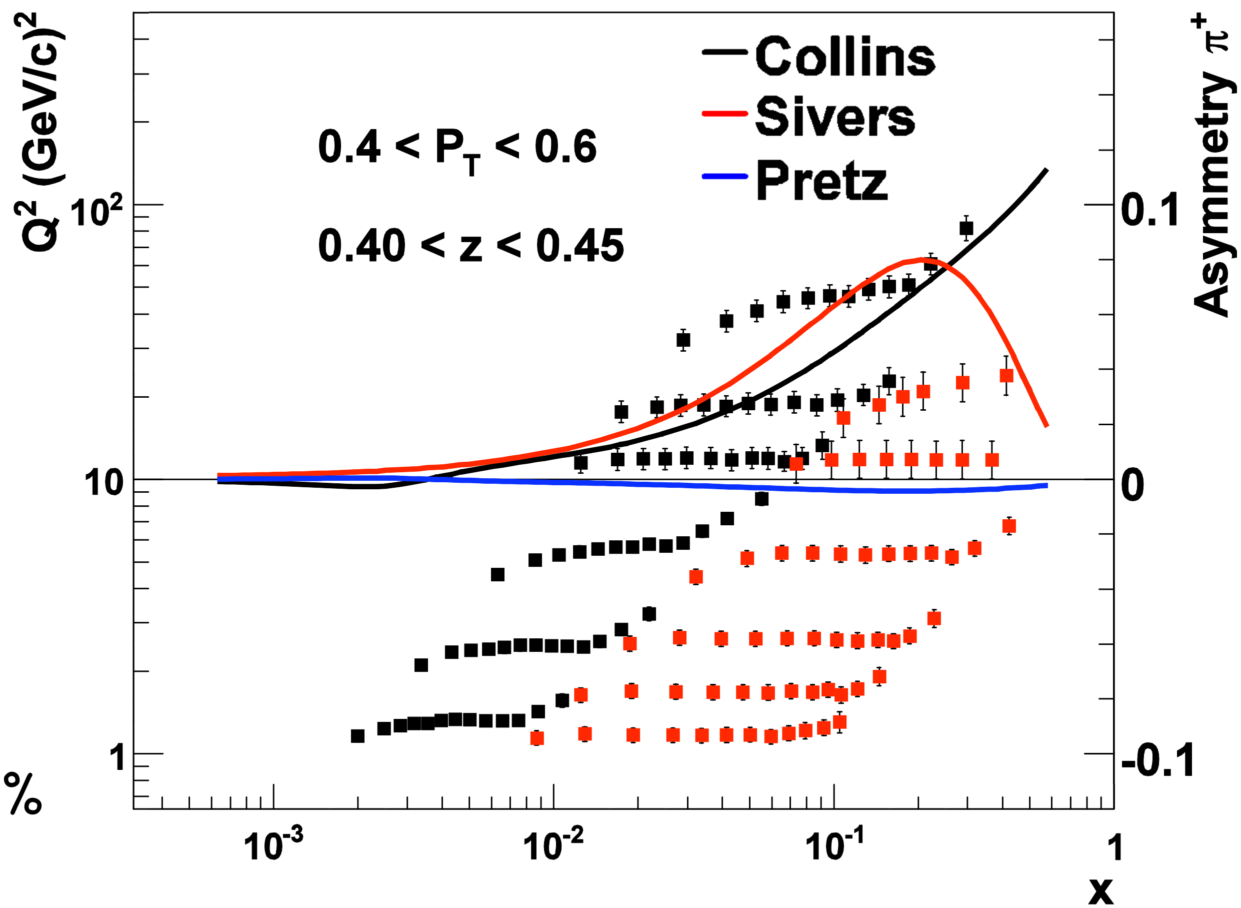
  3x10^{-3} , Q^2<10 GeV^2

  7x10^{-3} , Q^2>10 GeV^2

Polarization 80%
Overall efficiency 70%

z: 12 bins 0.2 - 0.8
P_T: 5 bins 0-1 GeV

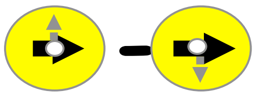
(Also π^-)



φ_h angular coverage incuded
Average of Collins/Sivers/Pretzelosity projections
Still with θ_h <40 cut, needs to be updated

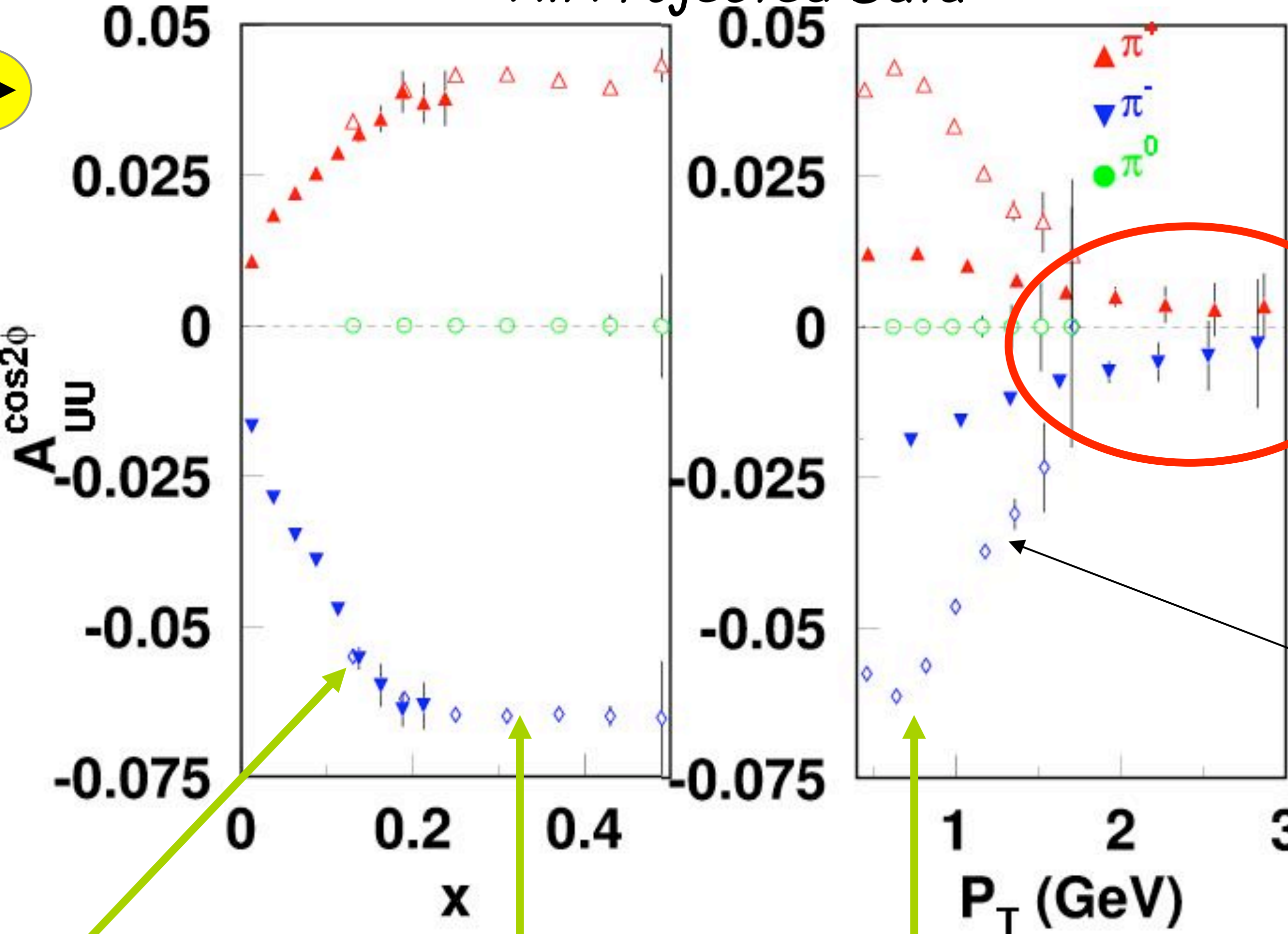
Correlation between Transverse Spin and Momentum of Quarks in Unpolarized Target

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$



(Harut Avakian, Antje Bruell)

All Projected Data



Perturbatively Calculable at Large p_T

Assumed 100 days of 10^{35} luminosity

Vanish like $1/p_T$ (Yuan)

Jefferson Lab 12

Exploring the Nature of Matter